Rethinking the Memory Hierarchy for Modern Languages

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MIT CSAIL

Memory systems expose an inexpressive interface

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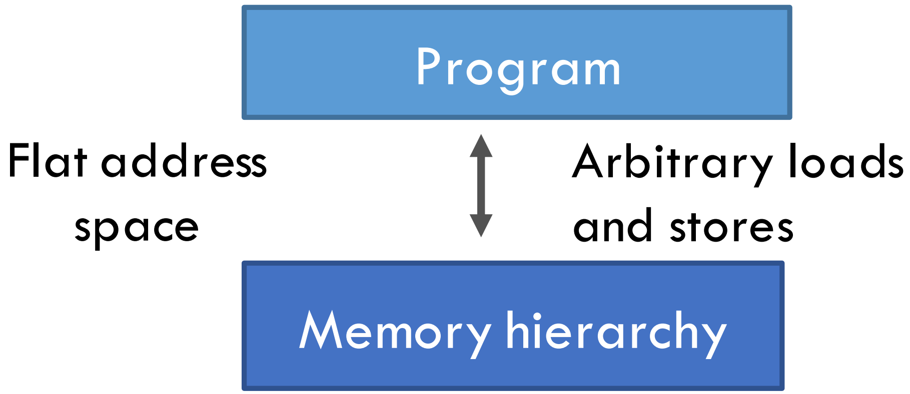

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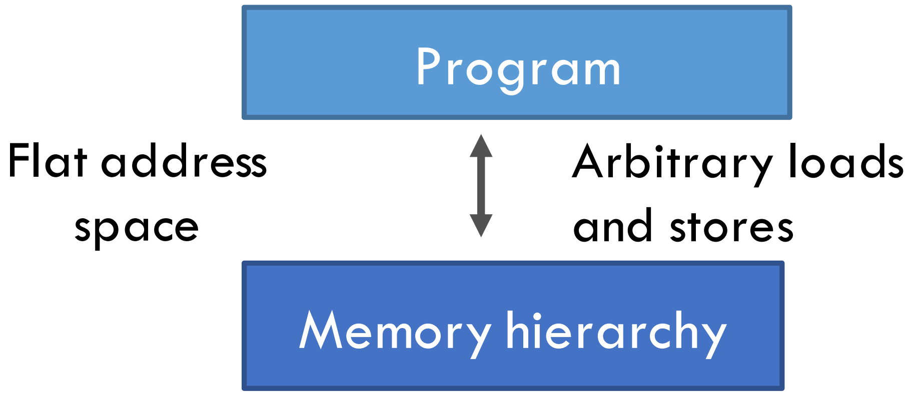
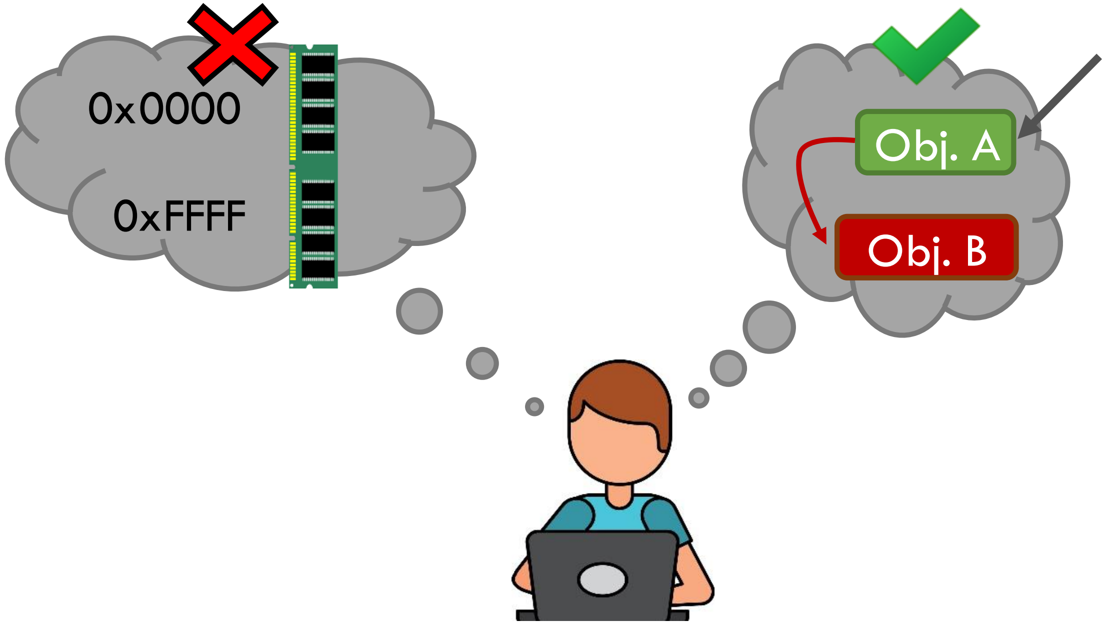
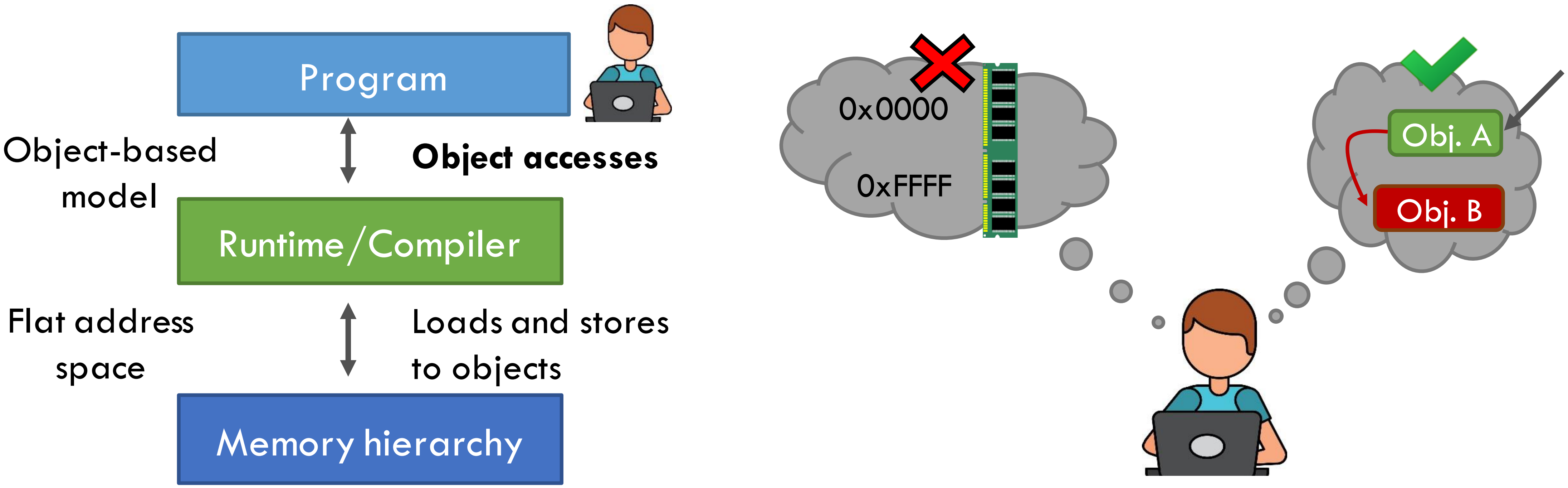




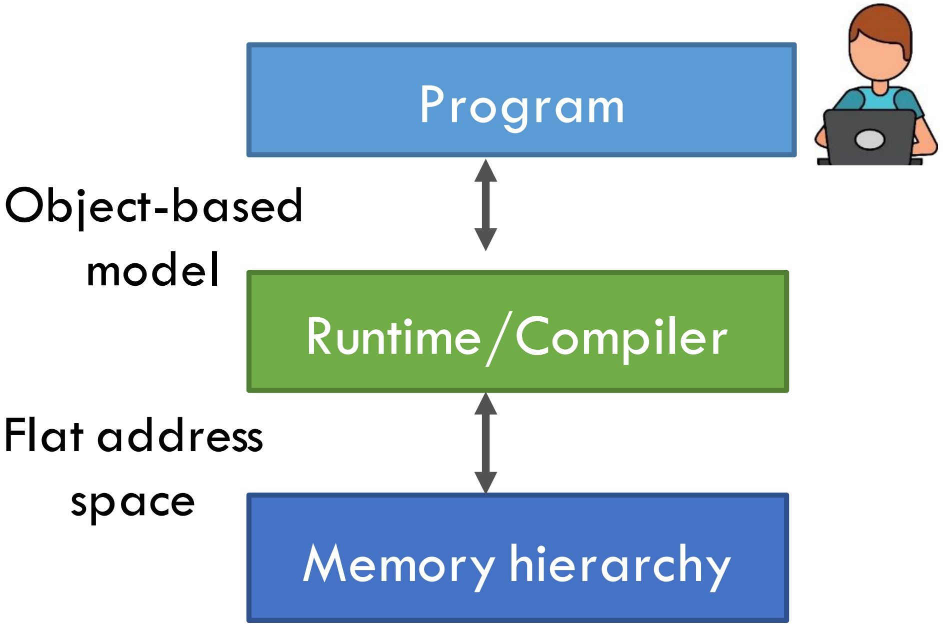
Programmers think of objects and pointers among objects

Modern languages expose an object-based memory model



- Strictly hiding the flat address space provides many benefits:
  - Memory safety prevents memory corruption bugs
  - Automatic memory management (garbage collection) simplifies programming

The inexpressive flat address space is inefficient



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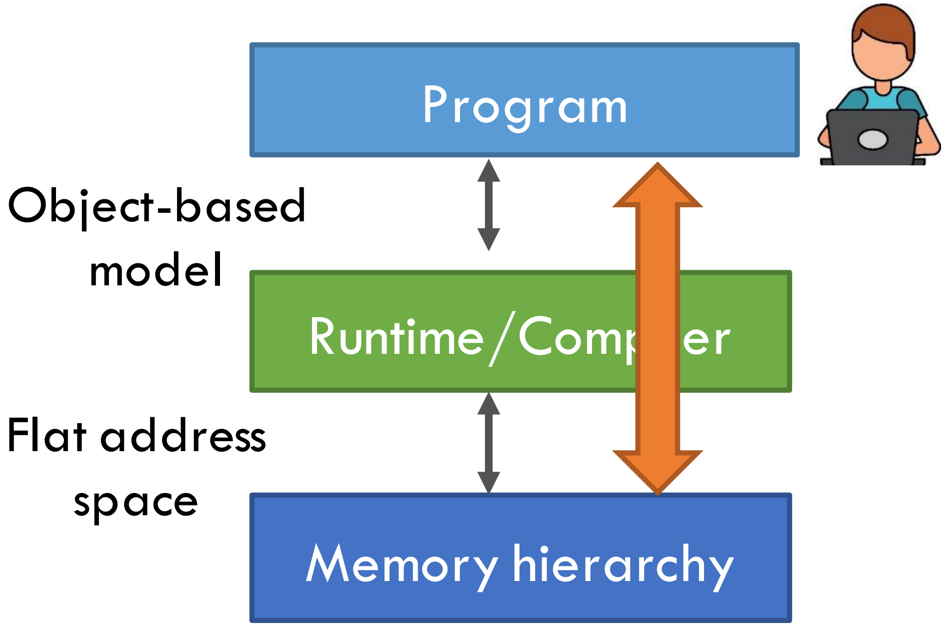

Semantic gap between programs and the memory hierarchy

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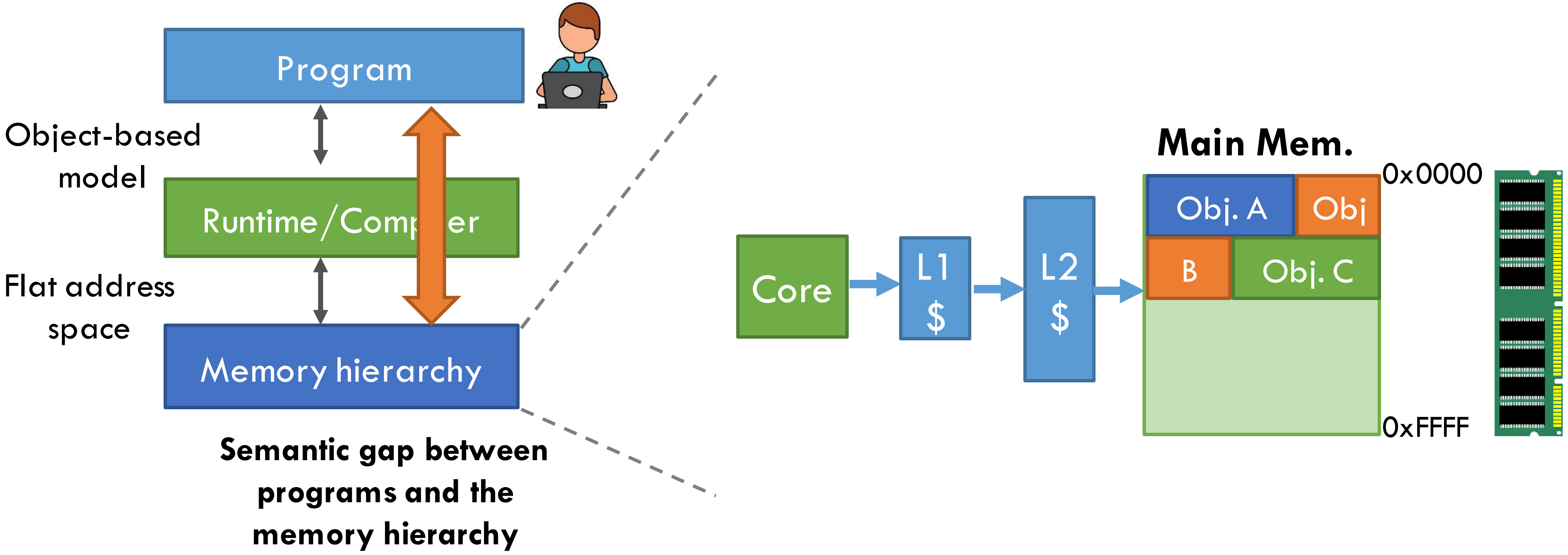

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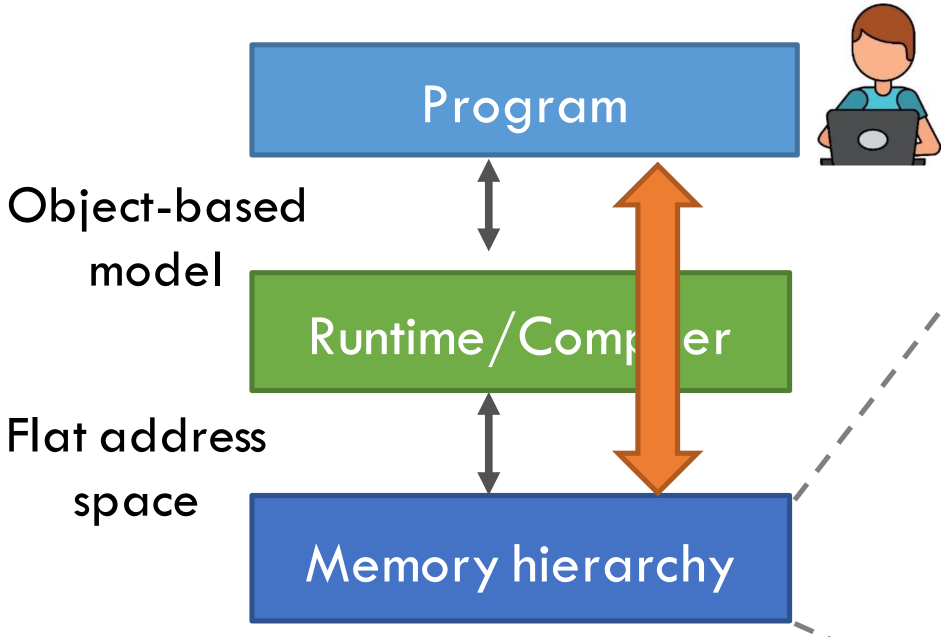

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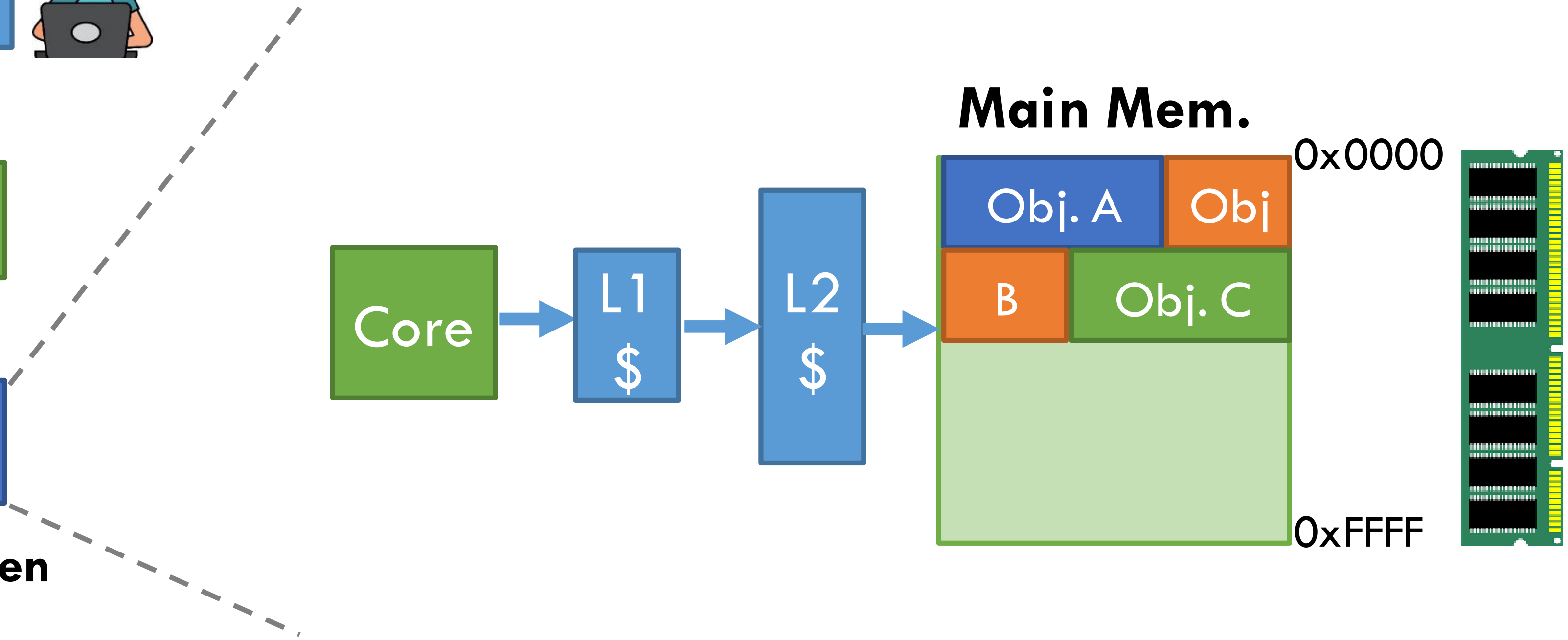

❌ Mismatch between objects and cache lines

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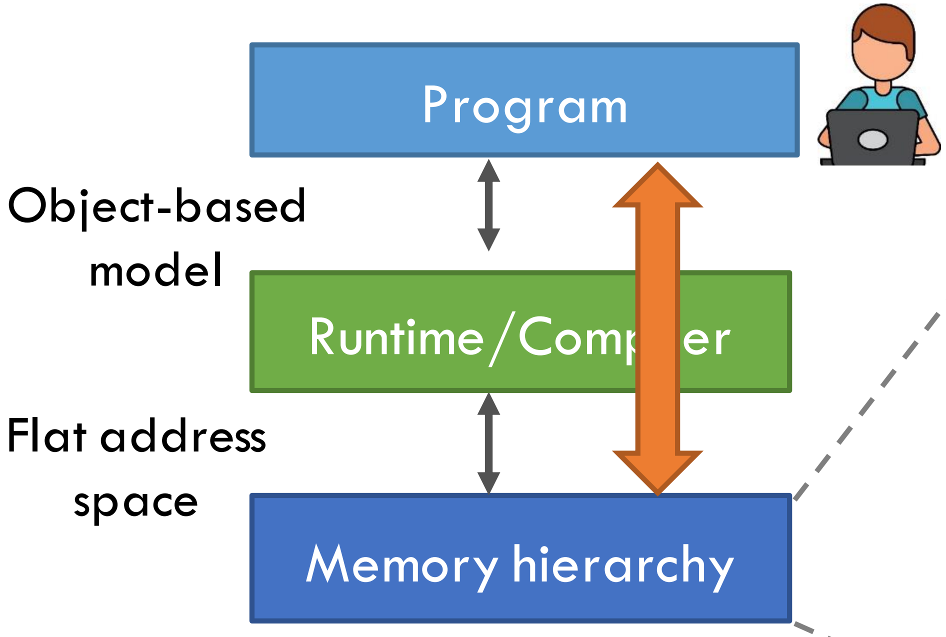

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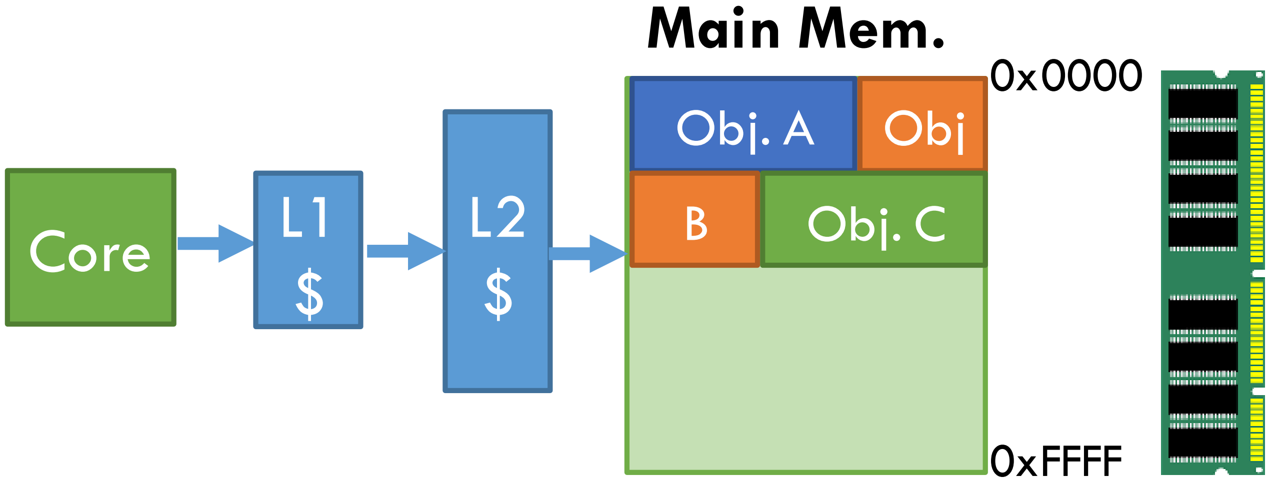

- ❌ Mismatch between objects and cache lines
- ❌ Costly associative lookups

Hotpads: An object-based memory hierarchy

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- A memory hierarchy designed from the ground up for *object-based programs*
  - Provides first-class support for objects and pointers in the ISA
  - Hides the memory layout from software and takes control over it

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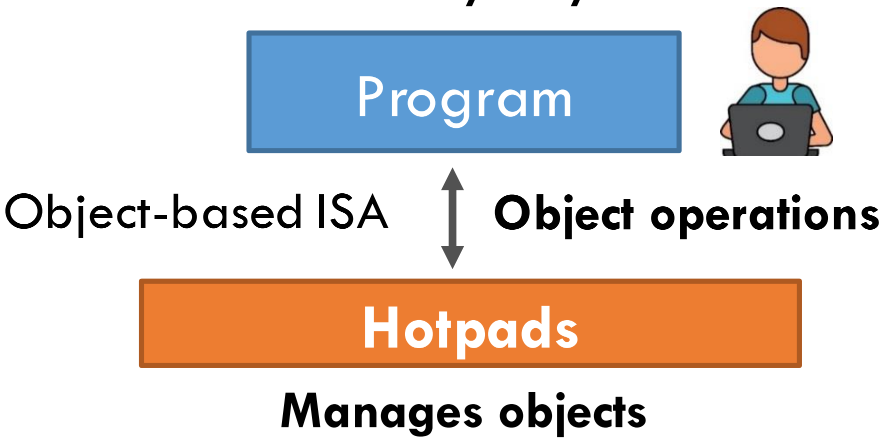

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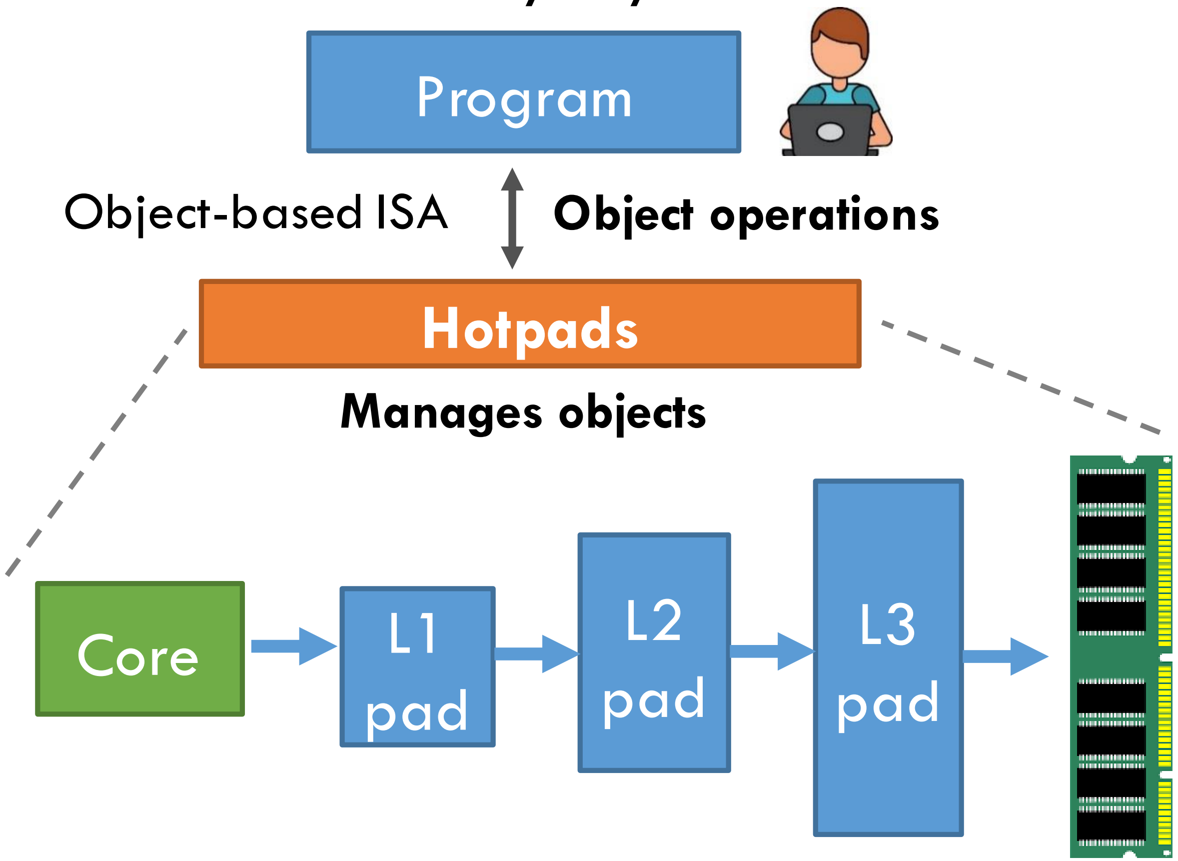

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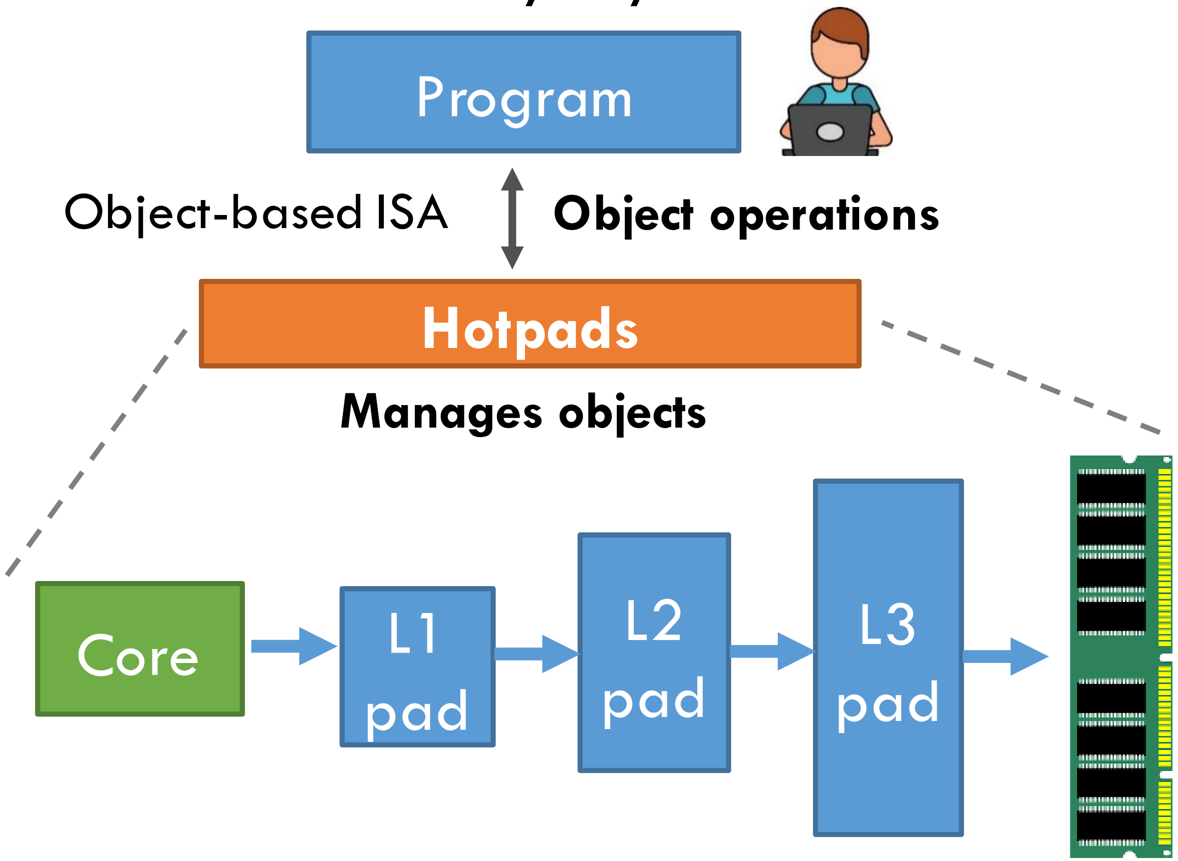

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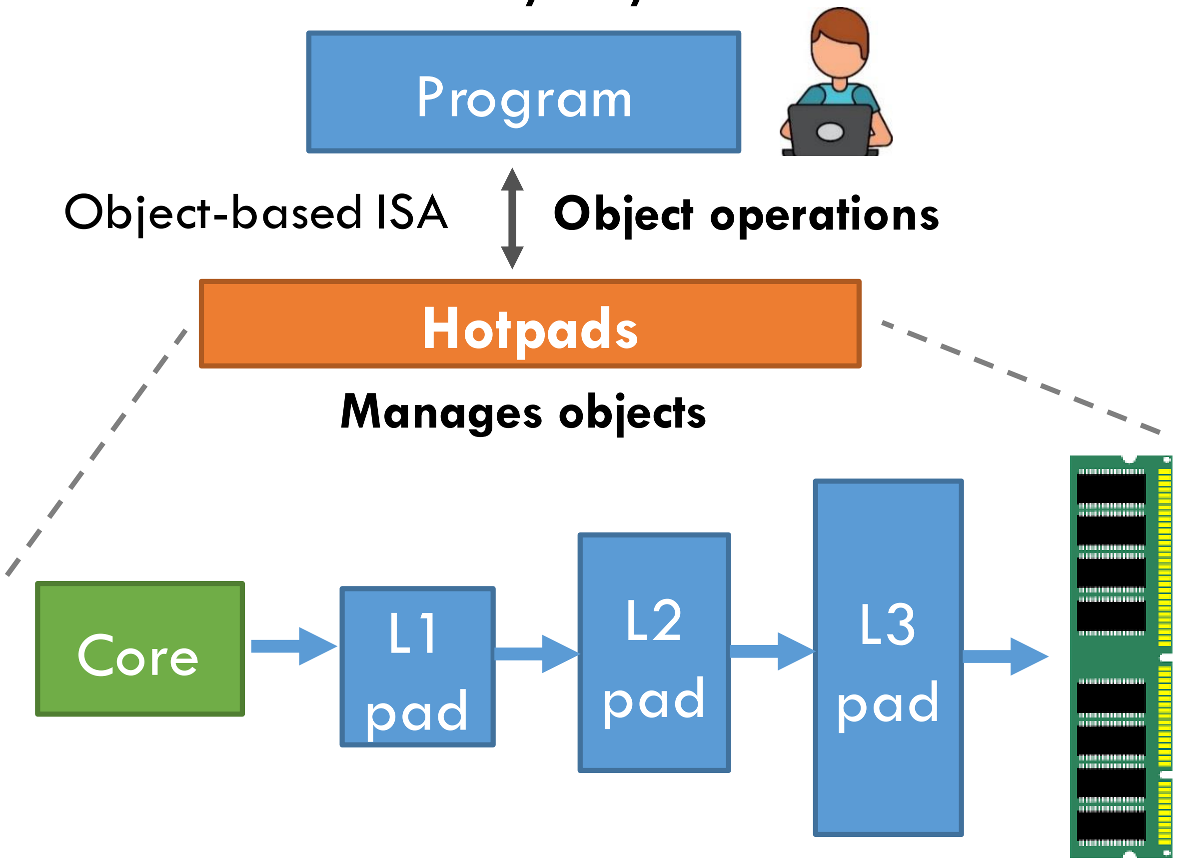

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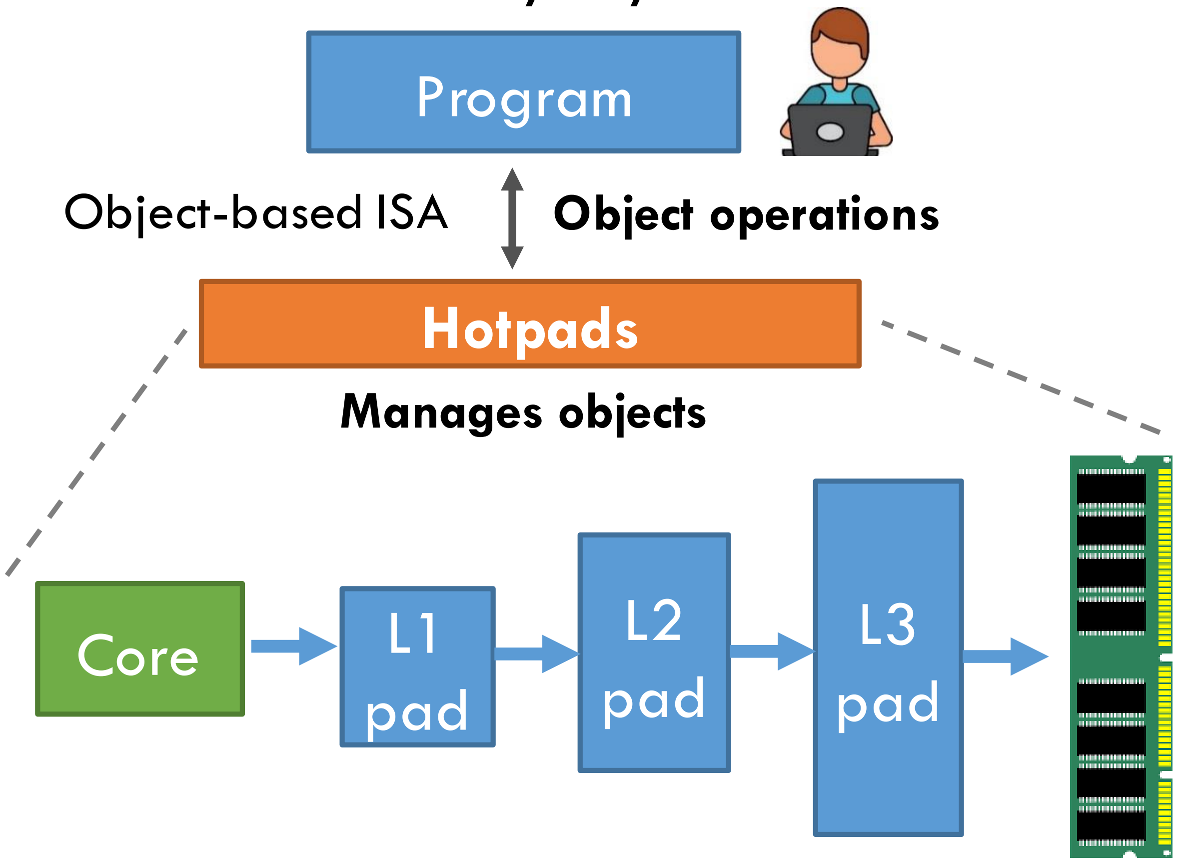

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Hotpads provides architectural support for in-hierarchy object allocation and recycling

Prior architectural support for object-based programs

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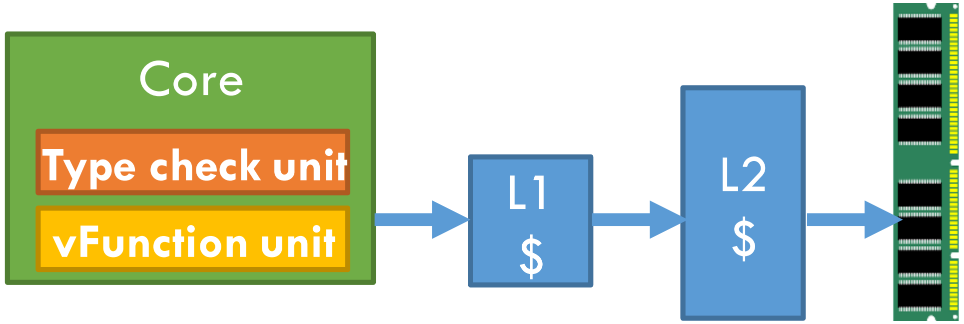
- Object-oriented/typed systems focus on **core microarchitecture design**
  - Accelerate virtual calls, object references and dynamic type checks



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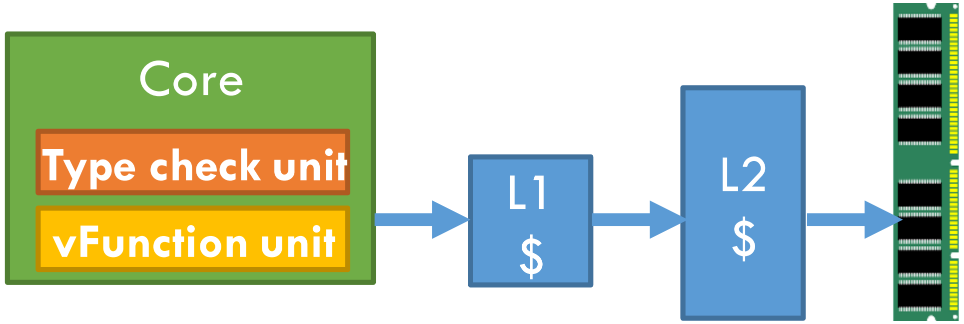
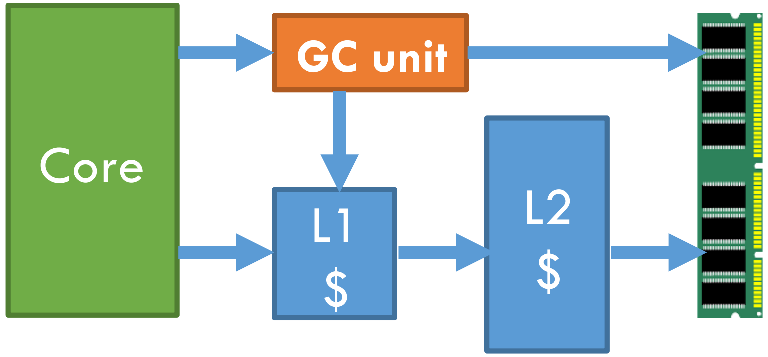


- Hardware accelerators for GC



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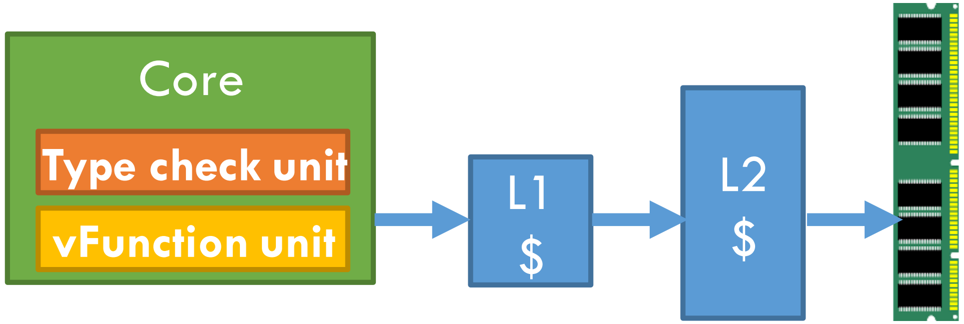

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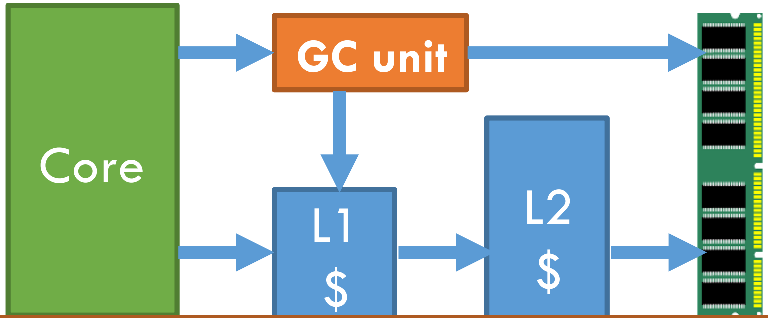

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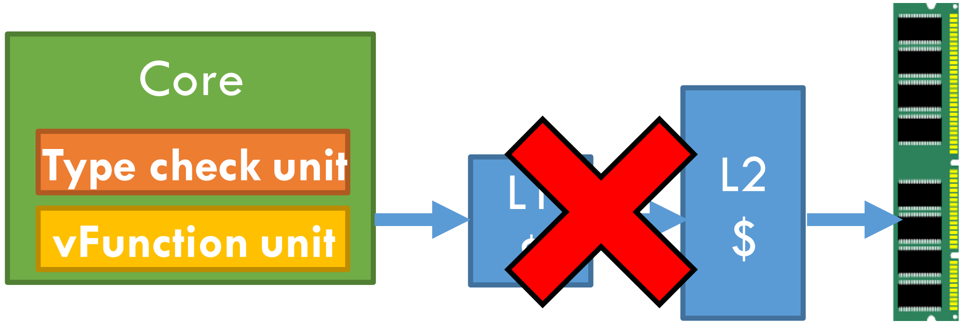

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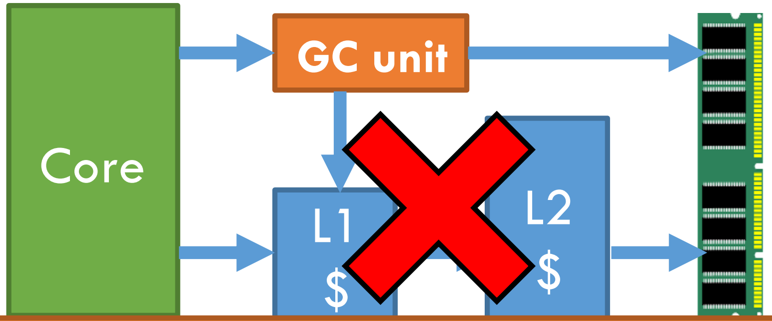

Prior work uses standard cache hierarchies

We focus on **redesigning the memory hierarchy**

Hotpads overview

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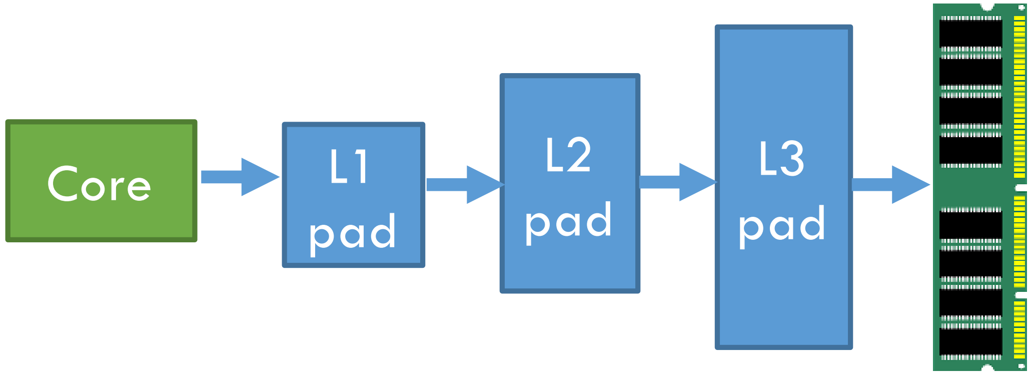

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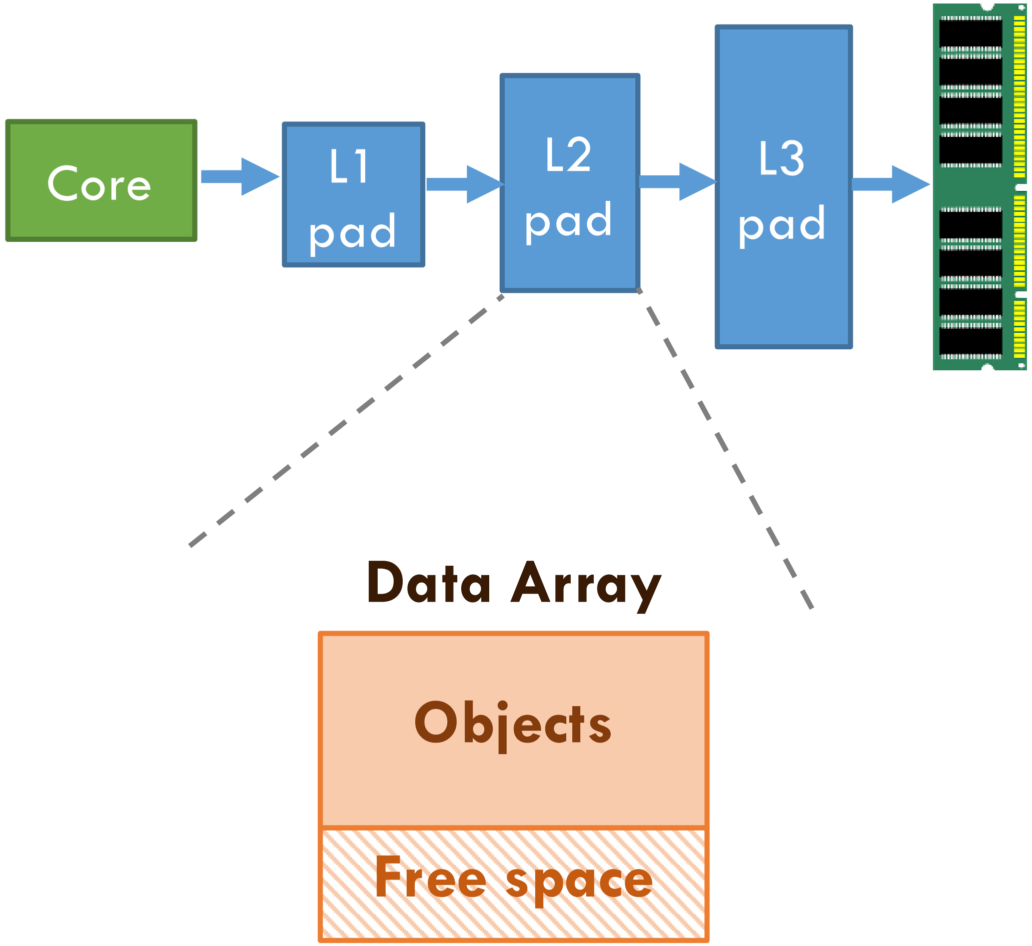

- Data array
  - Managed as a circular buffer using simple bump pointer allocation
  - Stores variable-sized objects compactly

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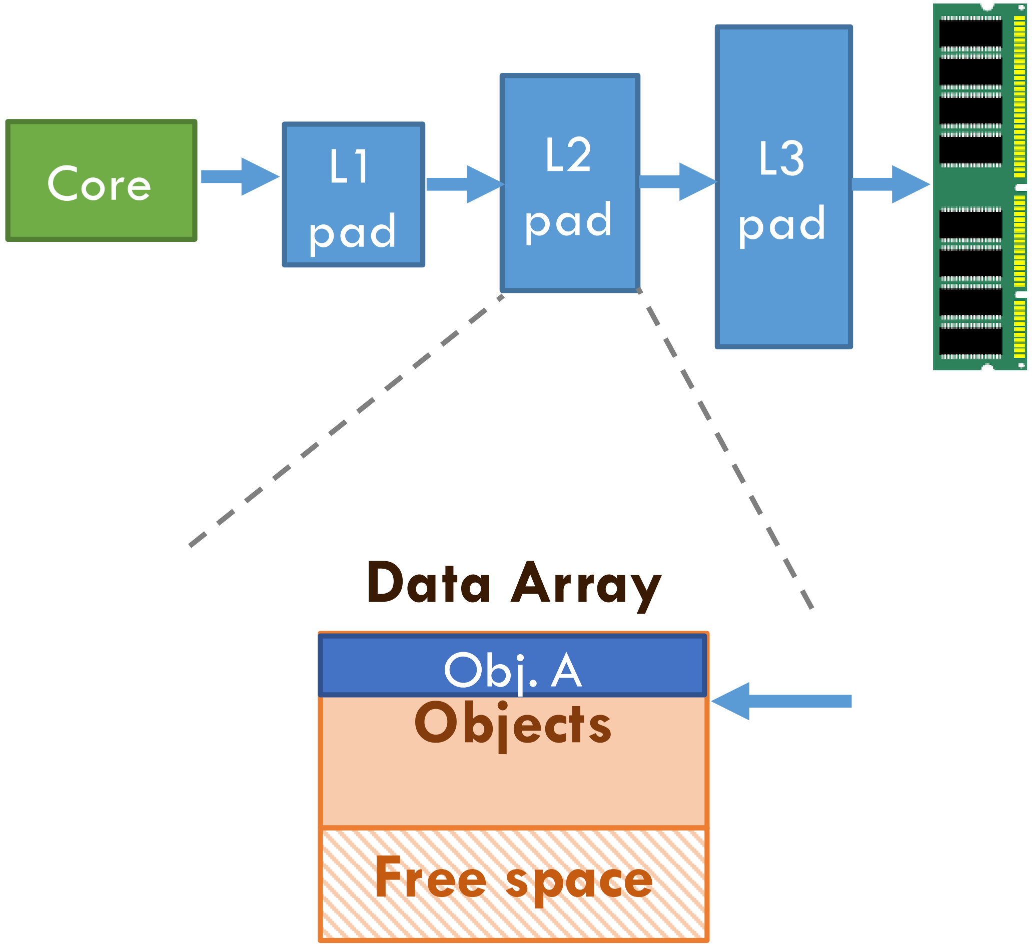

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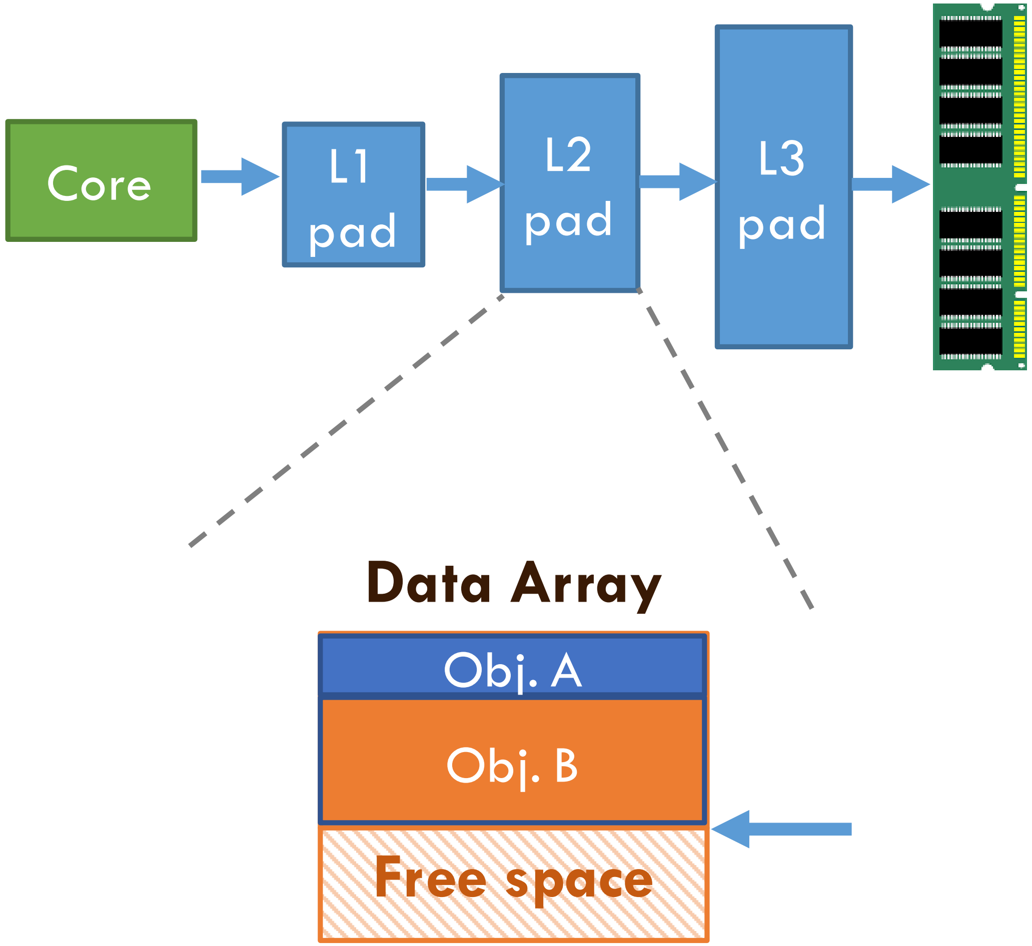

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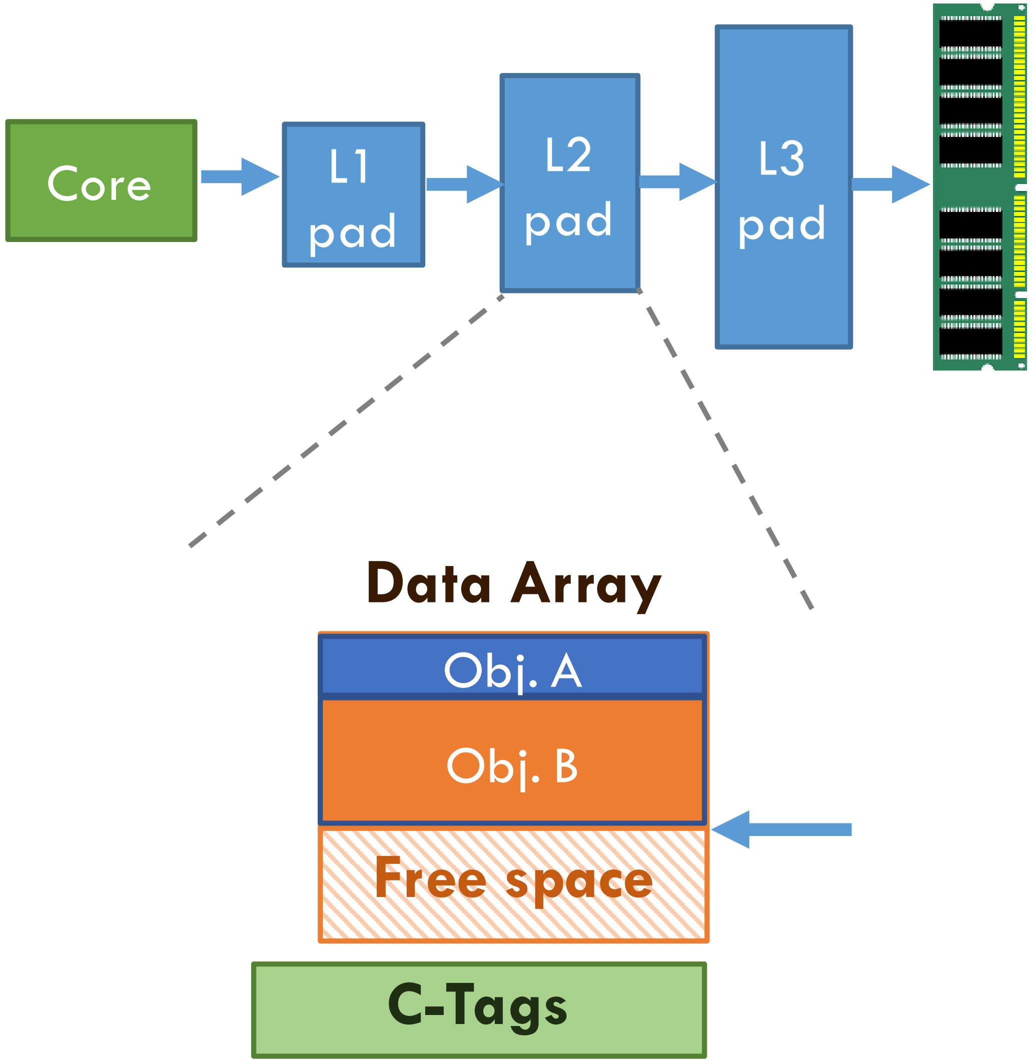

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  - Decoupled tag store used only for a fraction of accesses

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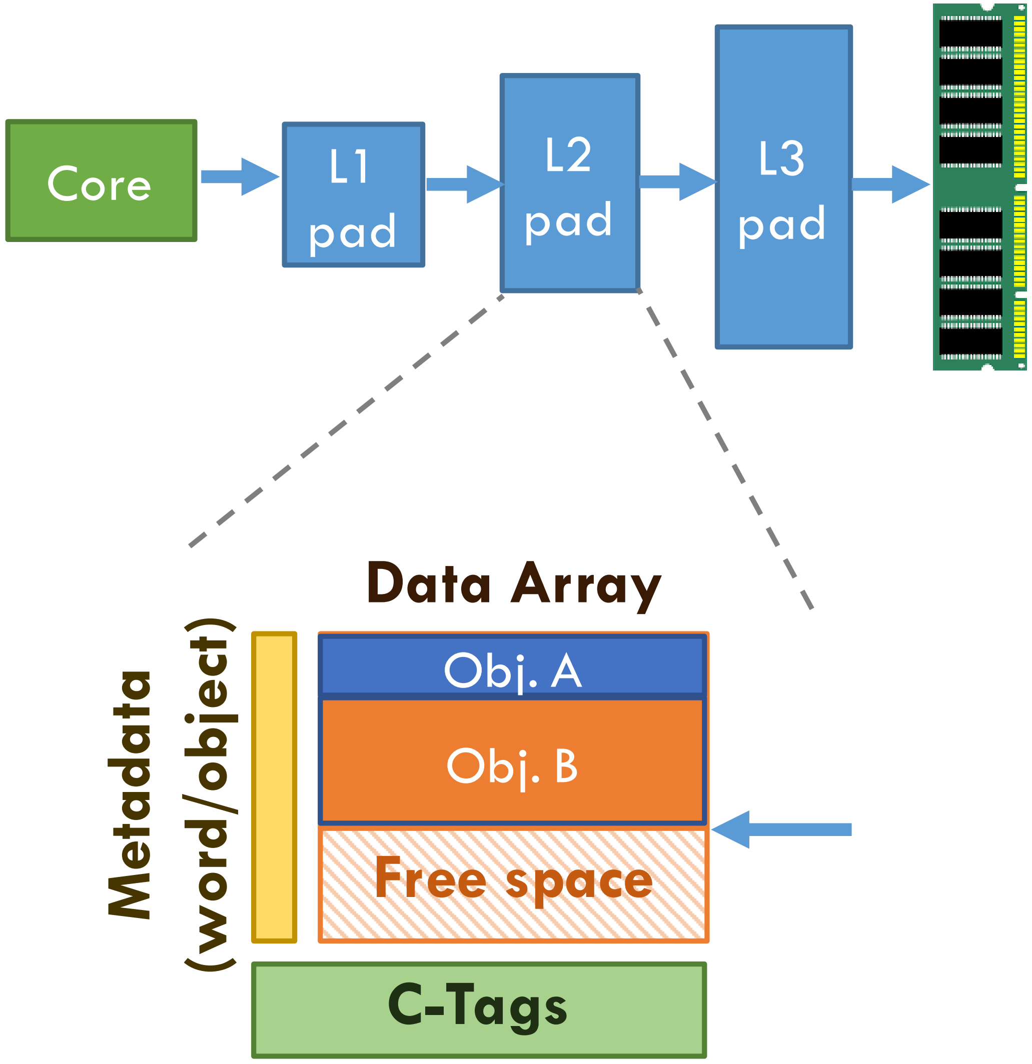

- Data array
  - Managed as a circular buffer using simple bump pointer allocation
  - Stores variable-sized objects compactly
- C-Tags
  - Decoupled tag store used only for a fraction of accesses
- Metadata
  - Pointer? valid? dirty? recently-used?

Hotpads example

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class Node {
    int value;
    Node next;
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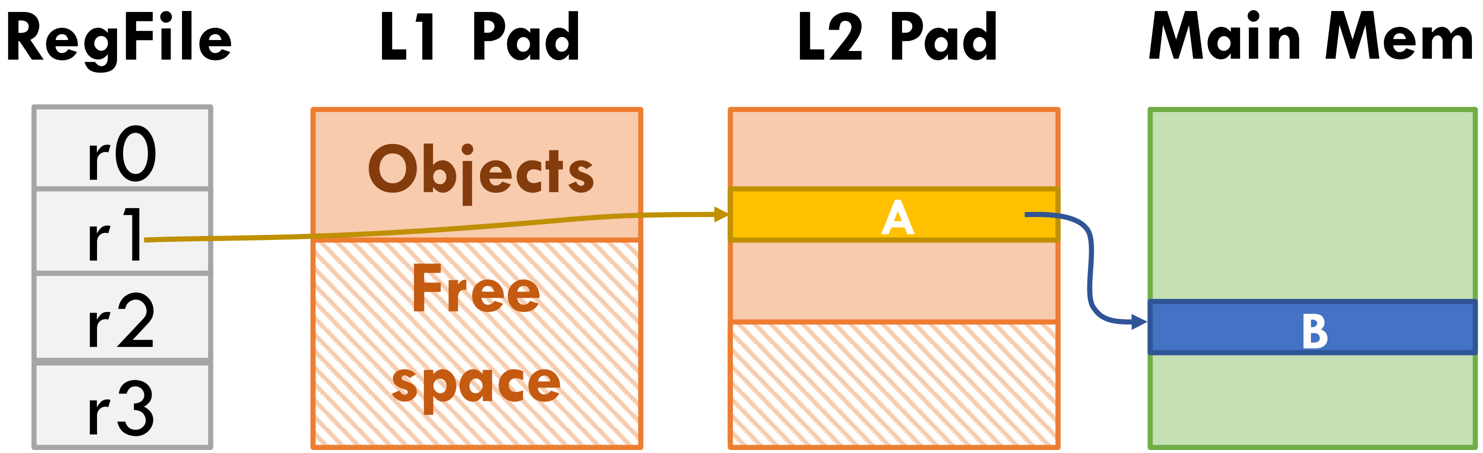

Initial state.

Hotpads moves object implicitly

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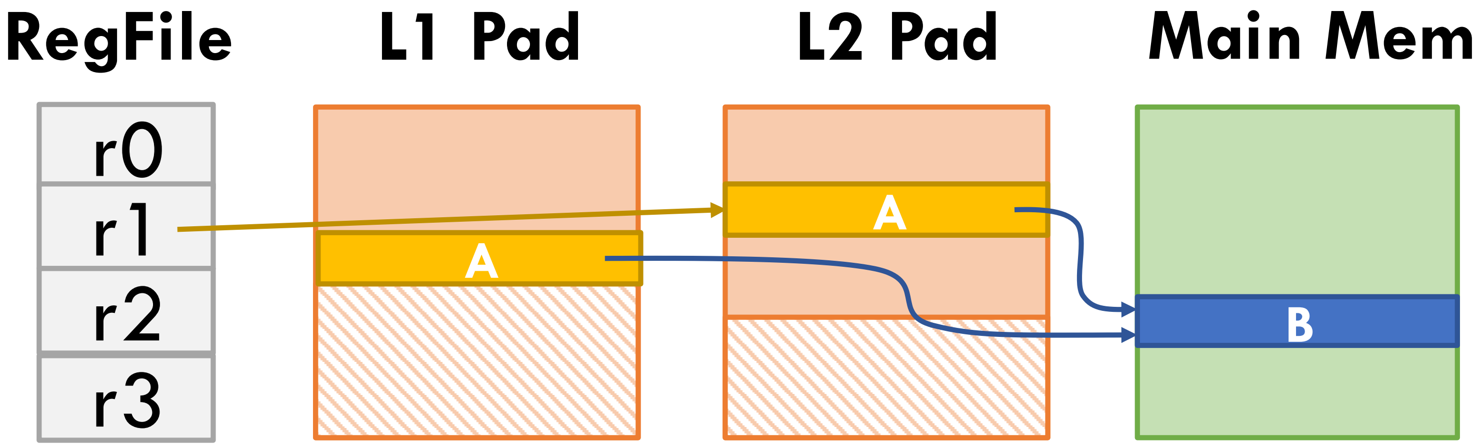

Program code:

```
int v = A.value;
```

Hotpads instructions:

```
ld r0, (r1).value
```

Core issues access to A.

A is copied into L1 pad.

Hotpads moves object implicitly

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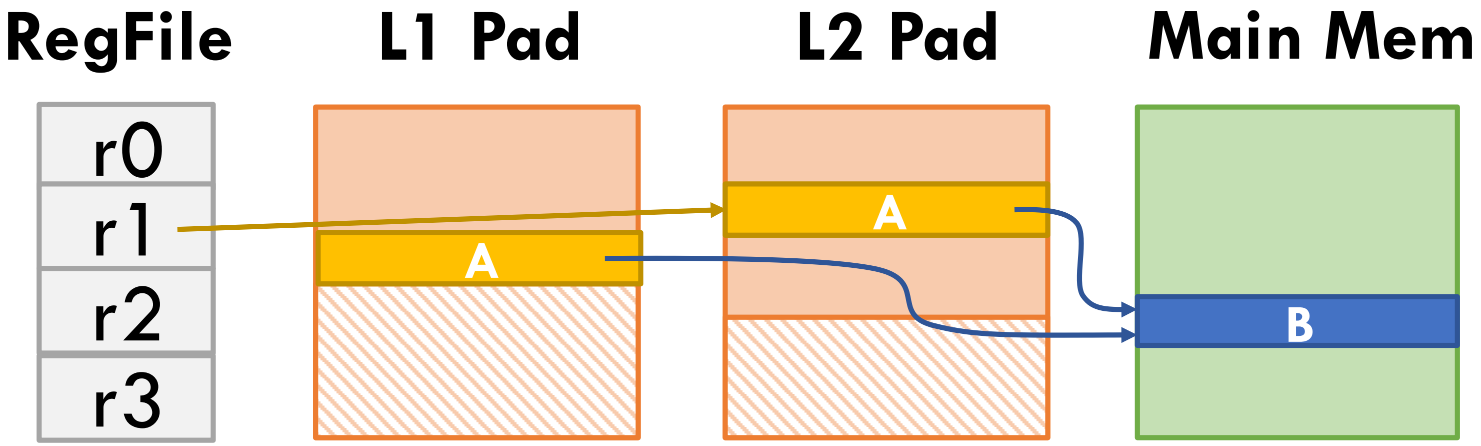

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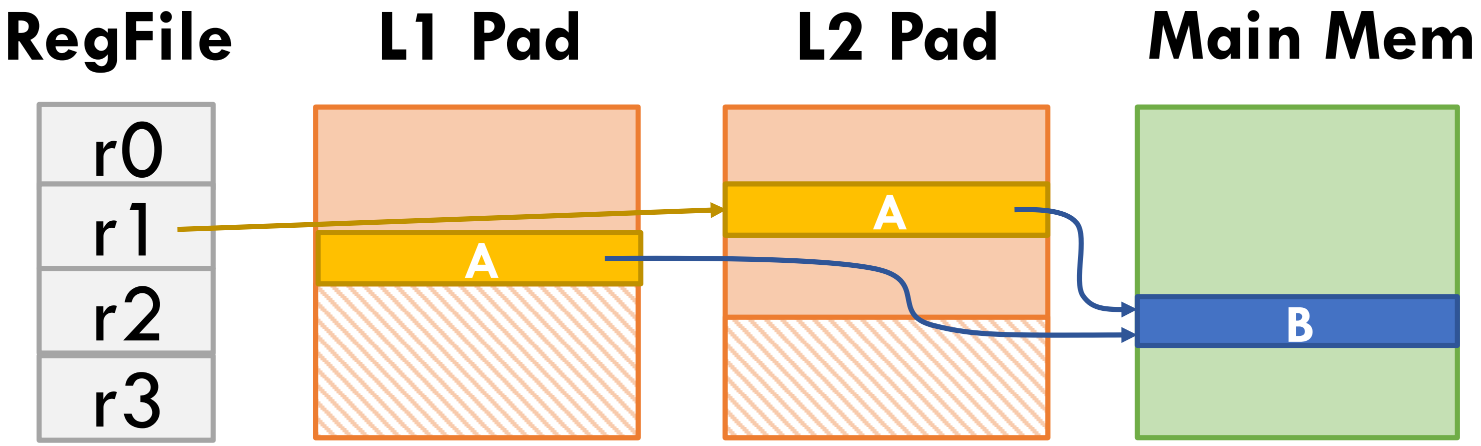

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- All loads/stores follow a single addressing mode: Base+offset
- Bump pointer allocation stores A compactly after other objects

Hotpads rewrites pointers to avoid associative lookups

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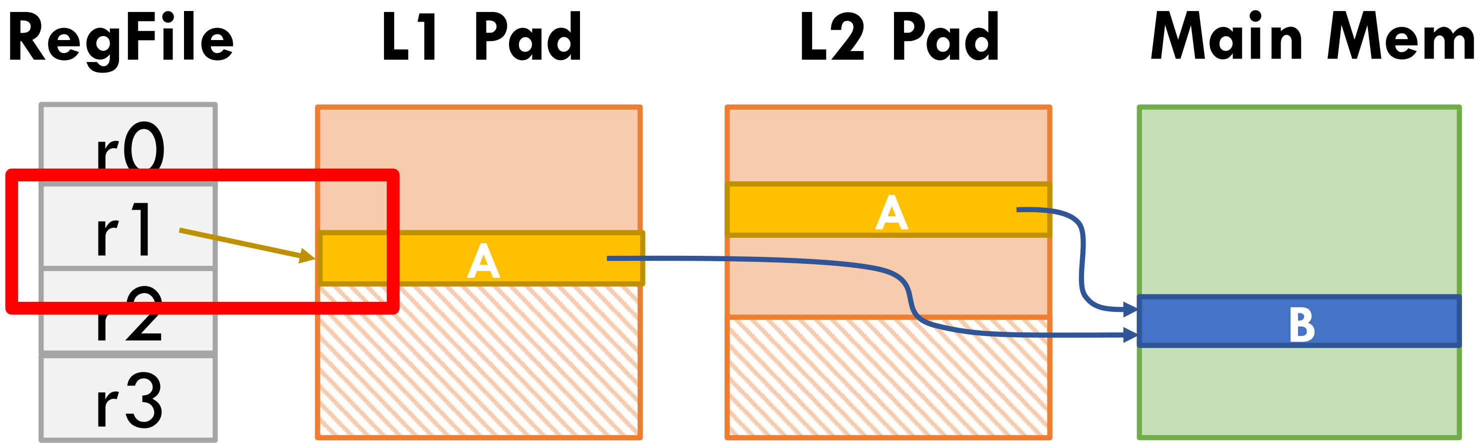

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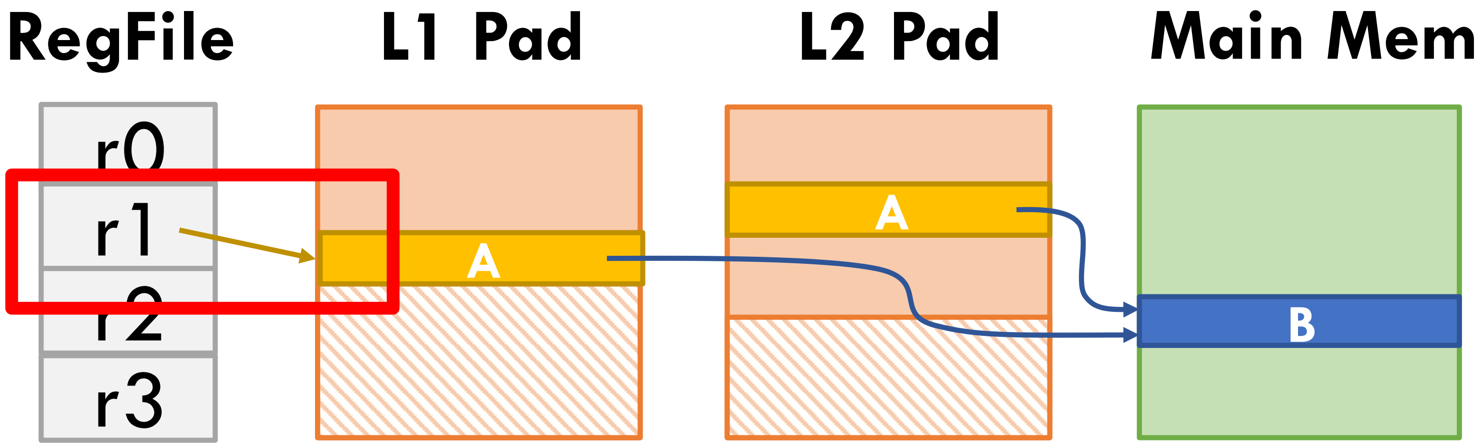

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- Subsequent dereferences of r1 access A's L1 copy directly, **without associative lookups (like a scratchpad)**

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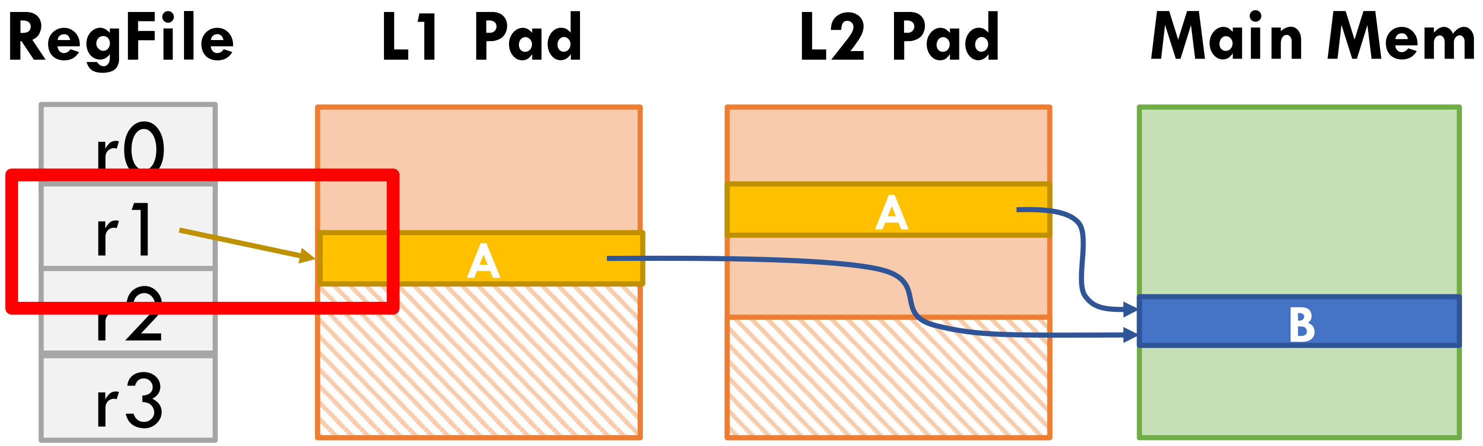

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- Subsequent dereferences of r1 access A's L1 copy directly, **without associative lookups (like a scratchpad)**
- Hotpads rewrites pointers safely because it hides the memory layout from software

Pointer rewriting applies to L1 pad data as well

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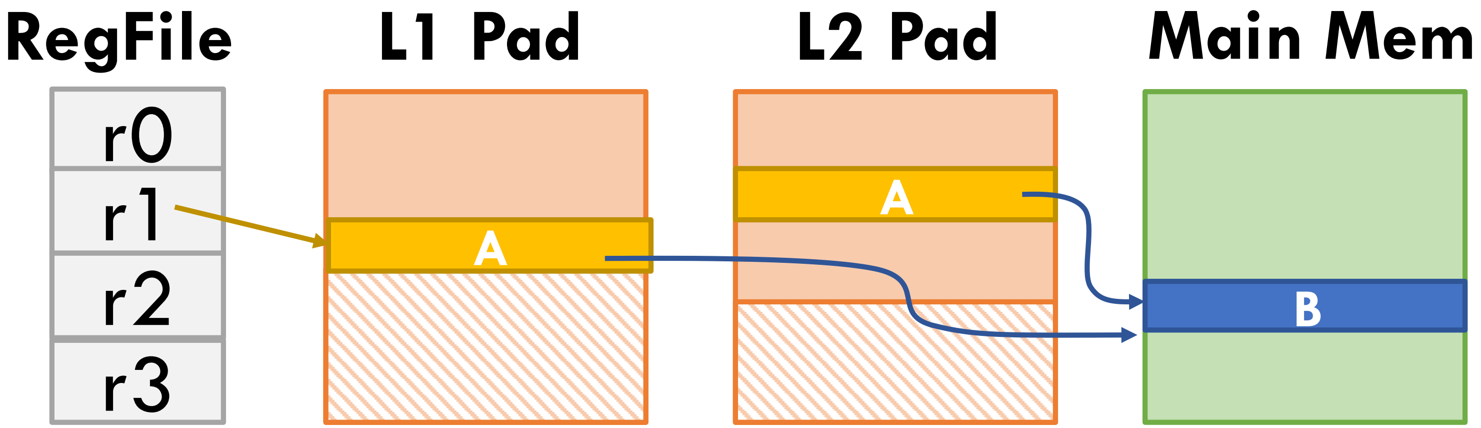

B copied into L1.

A's pointer is rewritten.

Program code:

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Hotpads instructions:

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derefptr r2, (r1).next
ld r3, (r2).value
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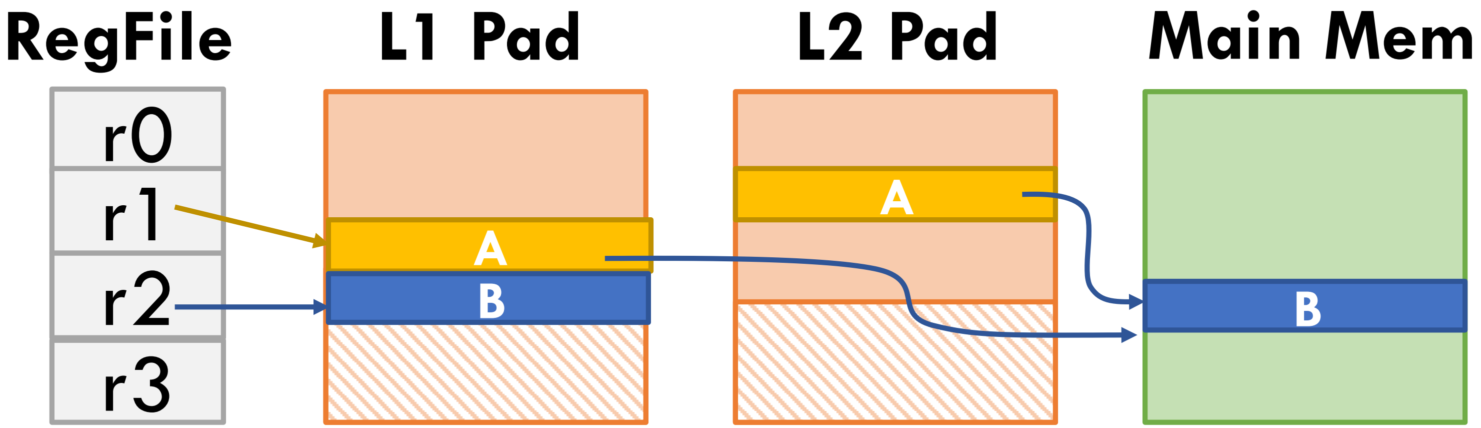

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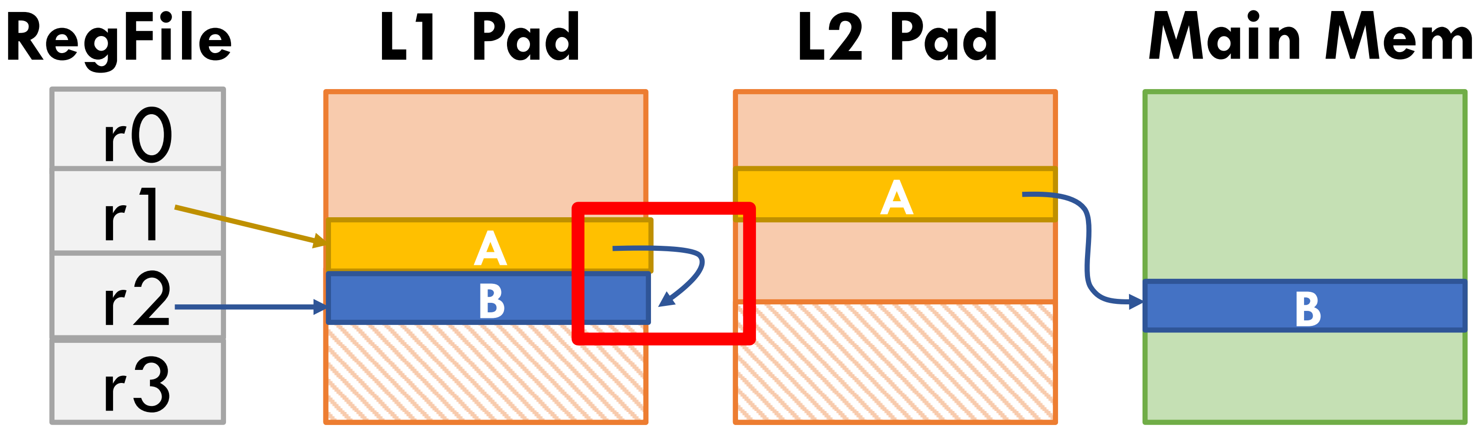

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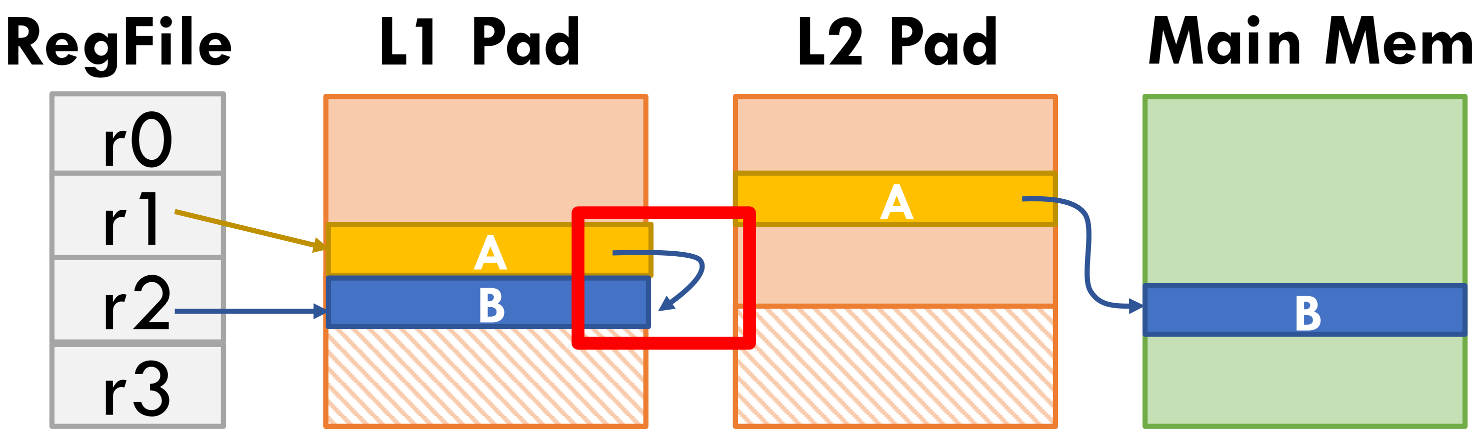

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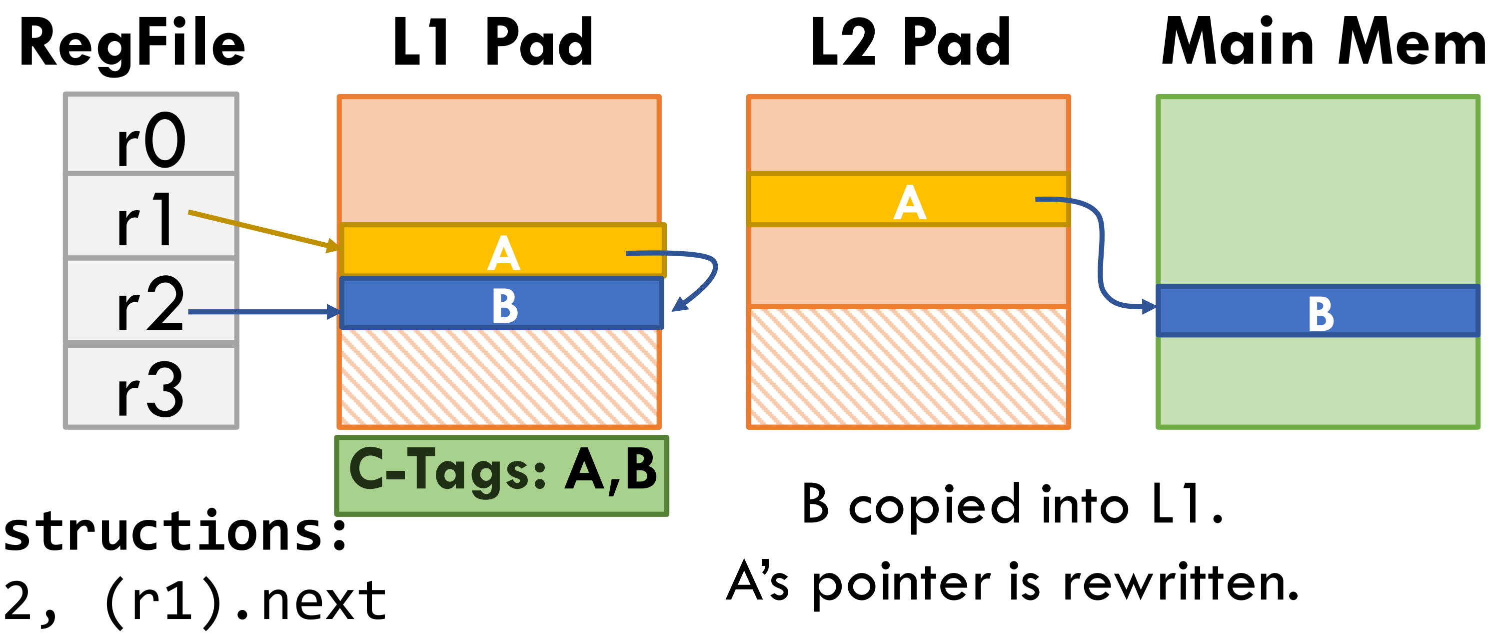

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```

- Subsequent dereferences of A.next access the L1 copy of B directly, **without associative lookups**
- C-tags let dereferencing other pointers of A and B find their L1 copies

Hotpads supports in-hierarchy object allocation

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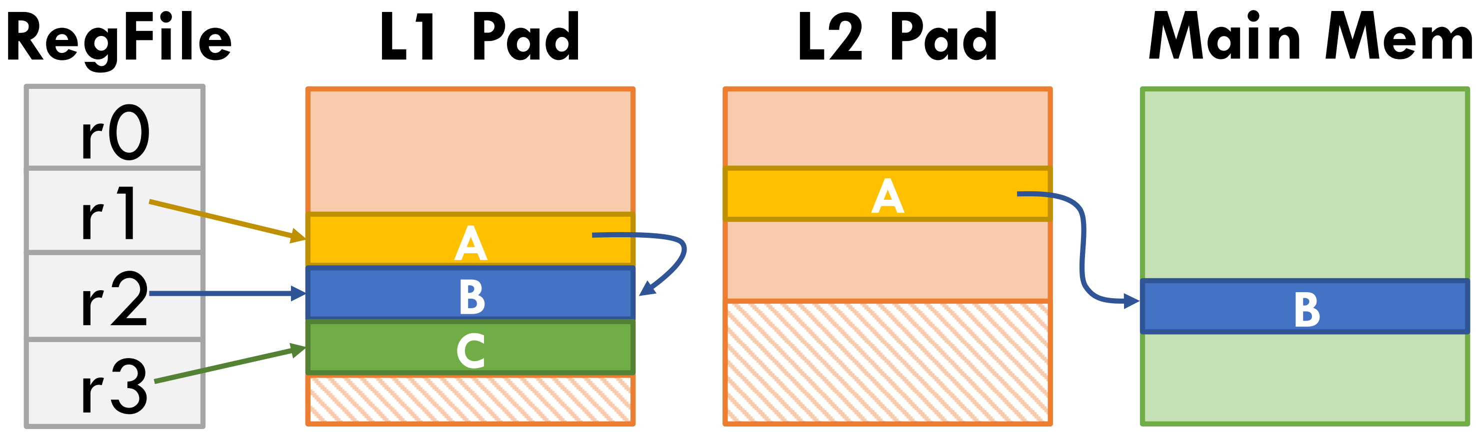
class Node {
    int value;
    Node next;
}
```



Core allocates new object C.

```
Program code:          Hotpads instructions:
Node C = new Node(); alloc r3, type=Node
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Hotpads supports in-hierarchy object allocation

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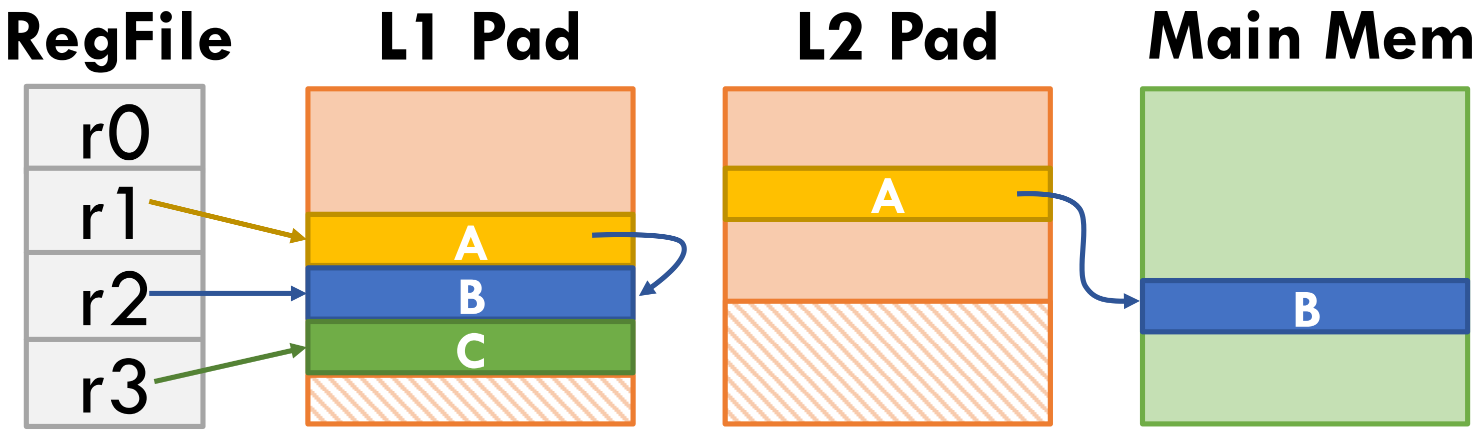


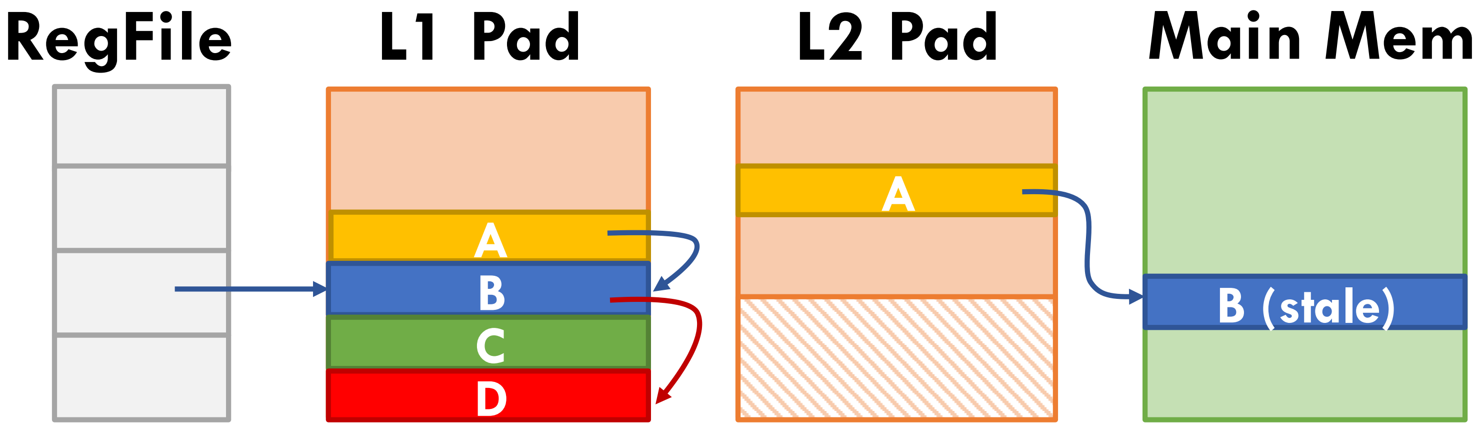
Core allocates new object C.

Program code:
`Node C = new Node();`

Hotpads instructions:
`alloc r3, type=Node`

- In-hierarchy allocation reduces data movement and requires no backing storage in main memory or larger pads

Hotpads unifies garbage collection and object evictions



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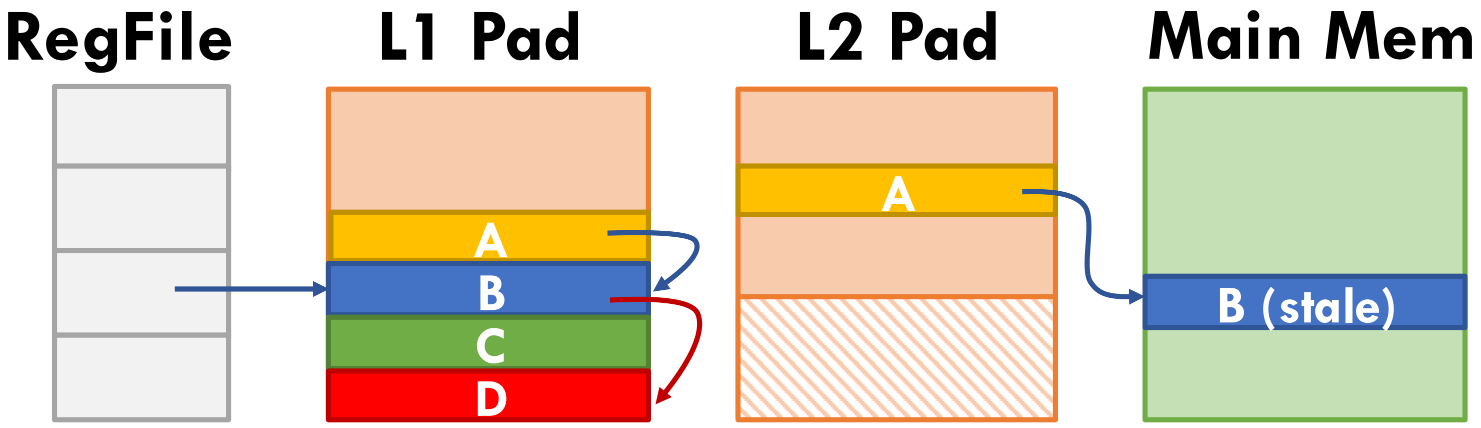

L1 pad is now full

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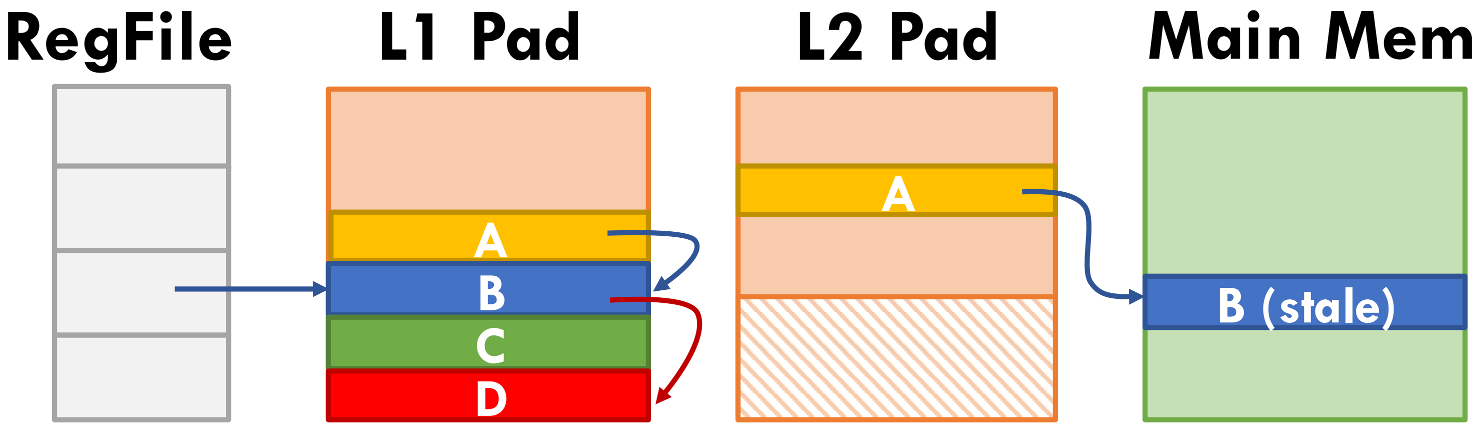

L1 pad is now full

- When a pad fills up, it triggers a collection-eviction (CE) to free space
  - Discards dead objects
  - Evicts live, non-recently used objects to the next level in bulk

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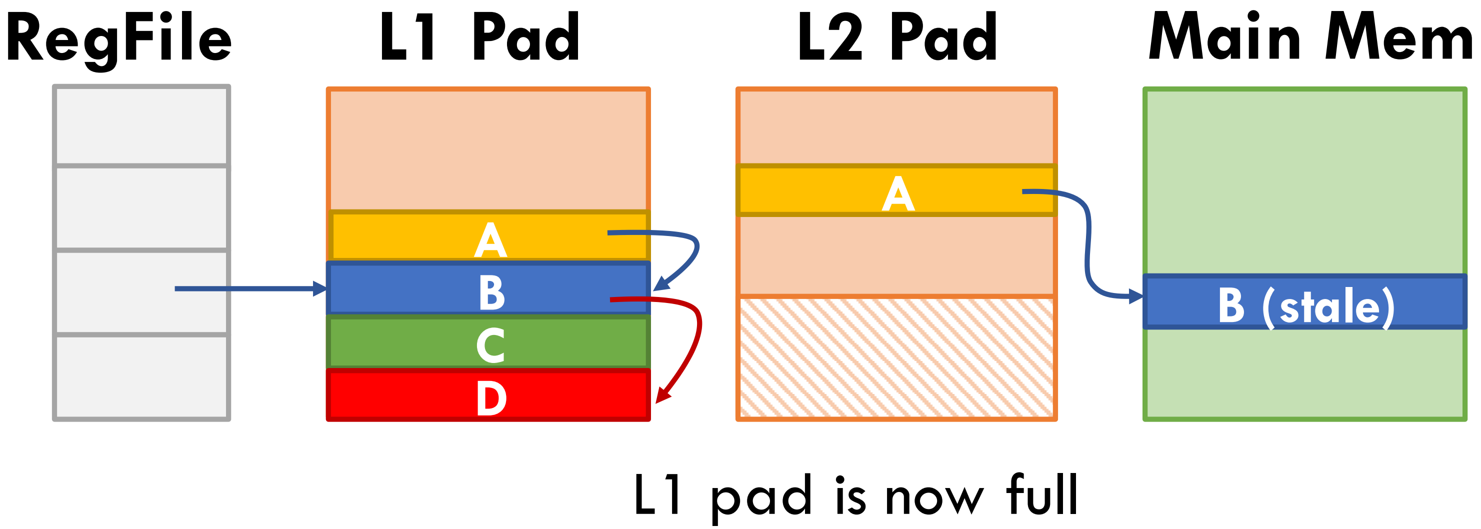
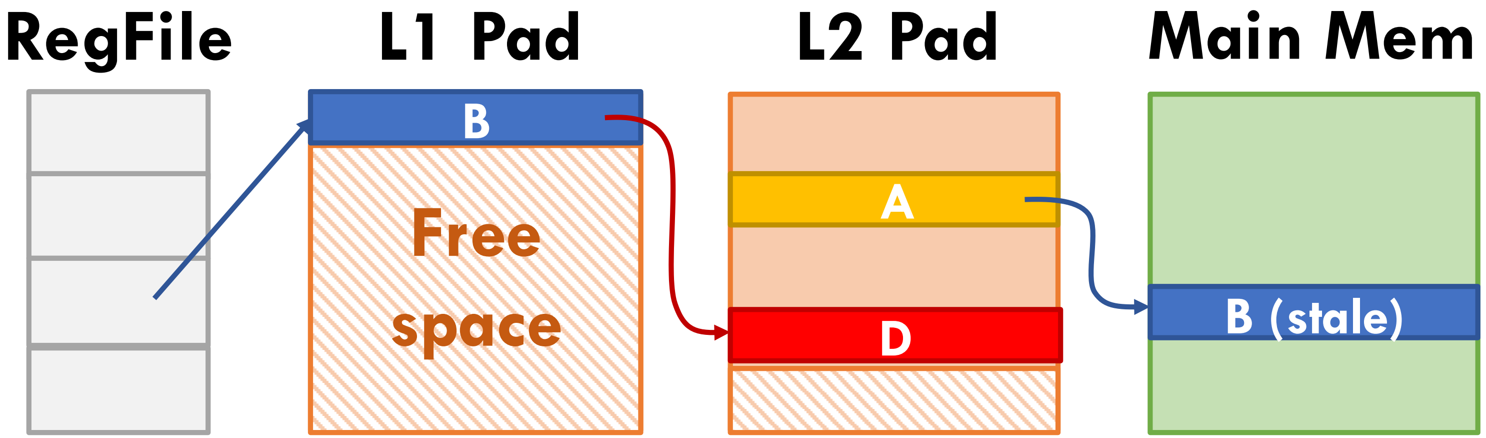


- When a pad fills up, it triggers a collection-eviction (CE) to free space
  - Discards dead objects
  - Evicts live, non-recently used objects to the next level in bulk
- C is dead (unreferenced). Other objects are live. Only B is recently used.

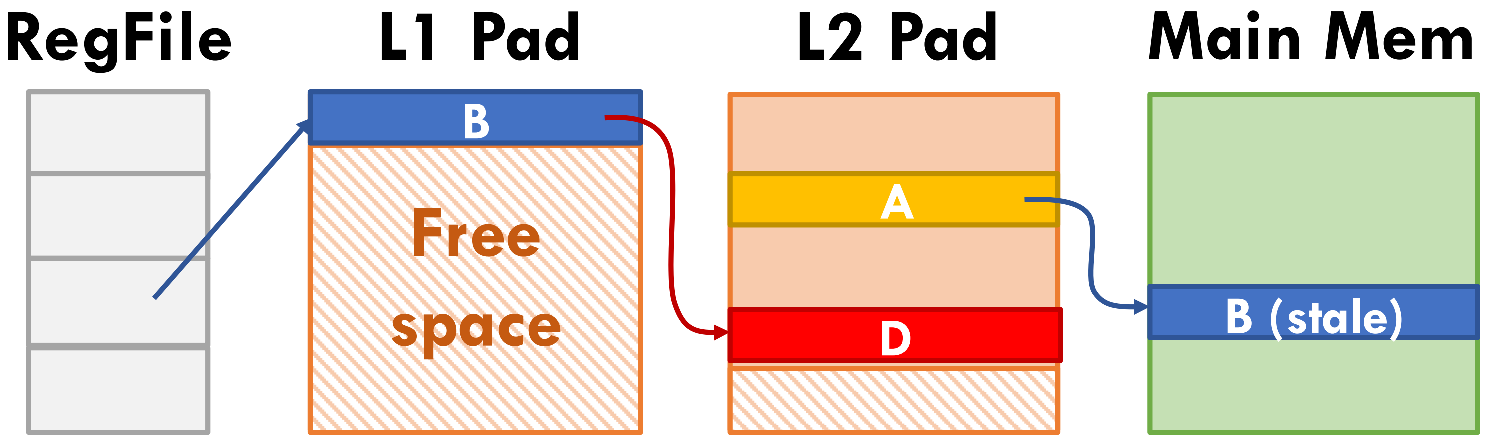
Hotpads unifies garbage collection and object evictions



L1 collection-eviction (CE) collects dead C and evicts live A & D to L2. It leaves a large contiguous chunk of free space

Hotpads unifies garbage collection and object evictions

- CEs happen concurrently with program execution and are hierarchical



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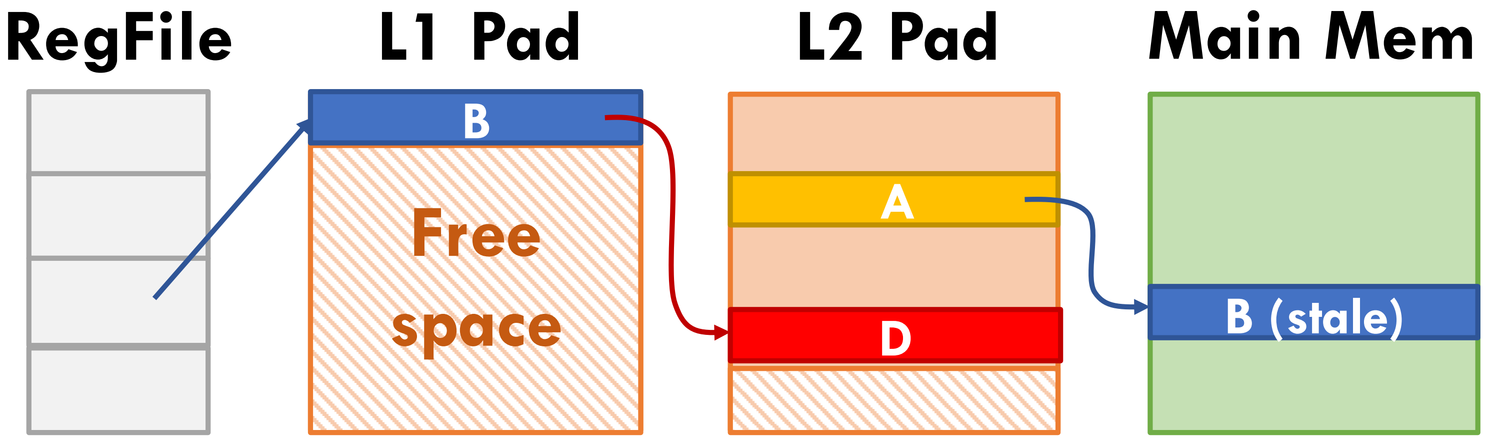

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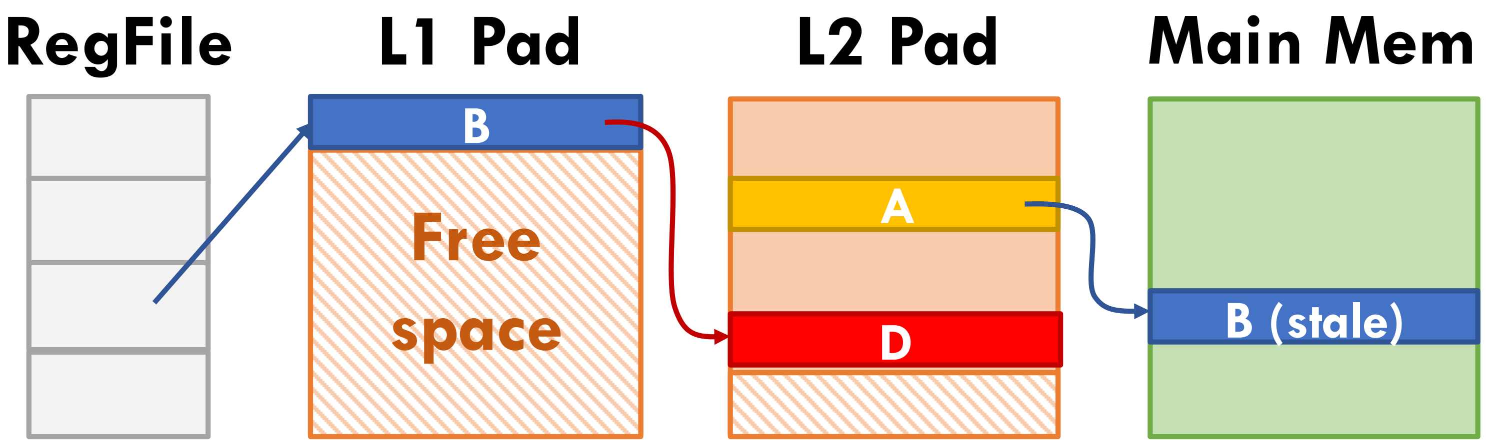

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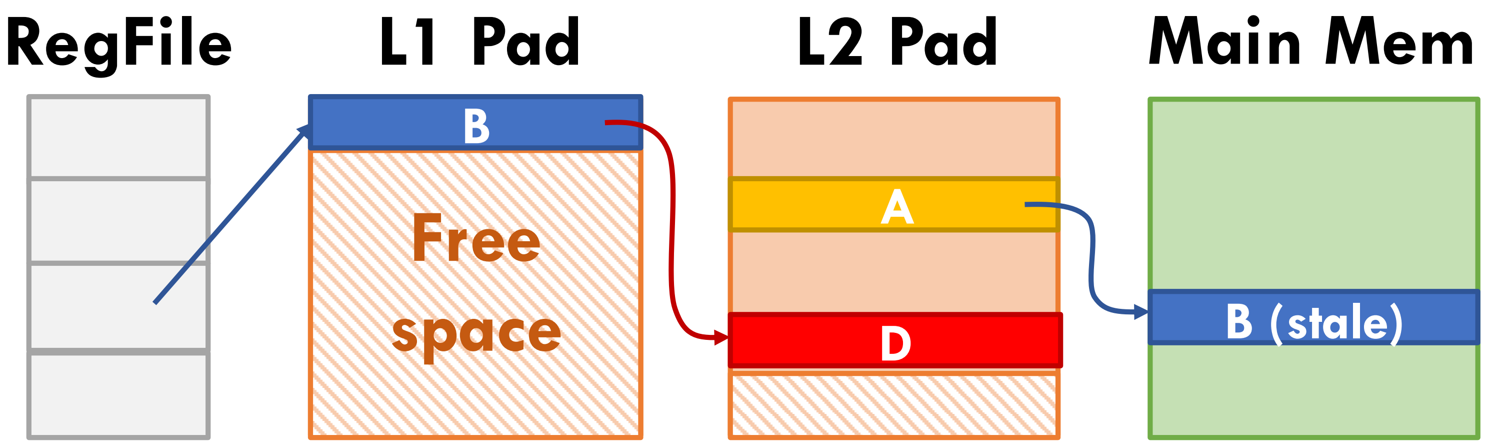

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Result: No need to check the L2 pad when performing a collection-eviction in the L1 pad.

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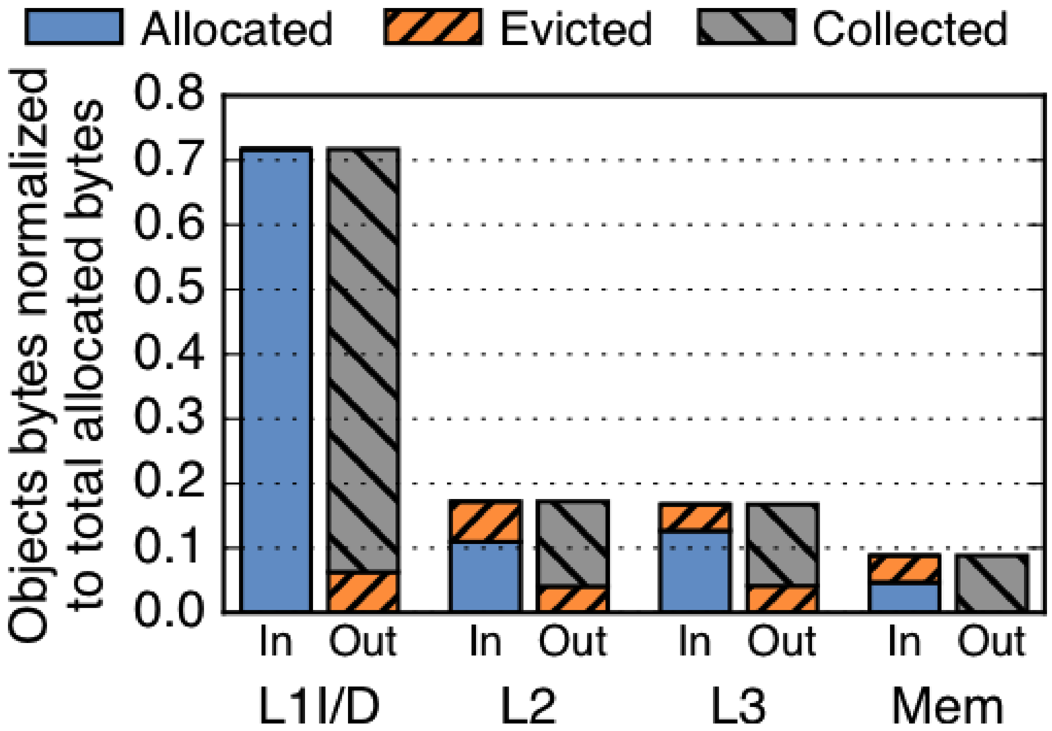

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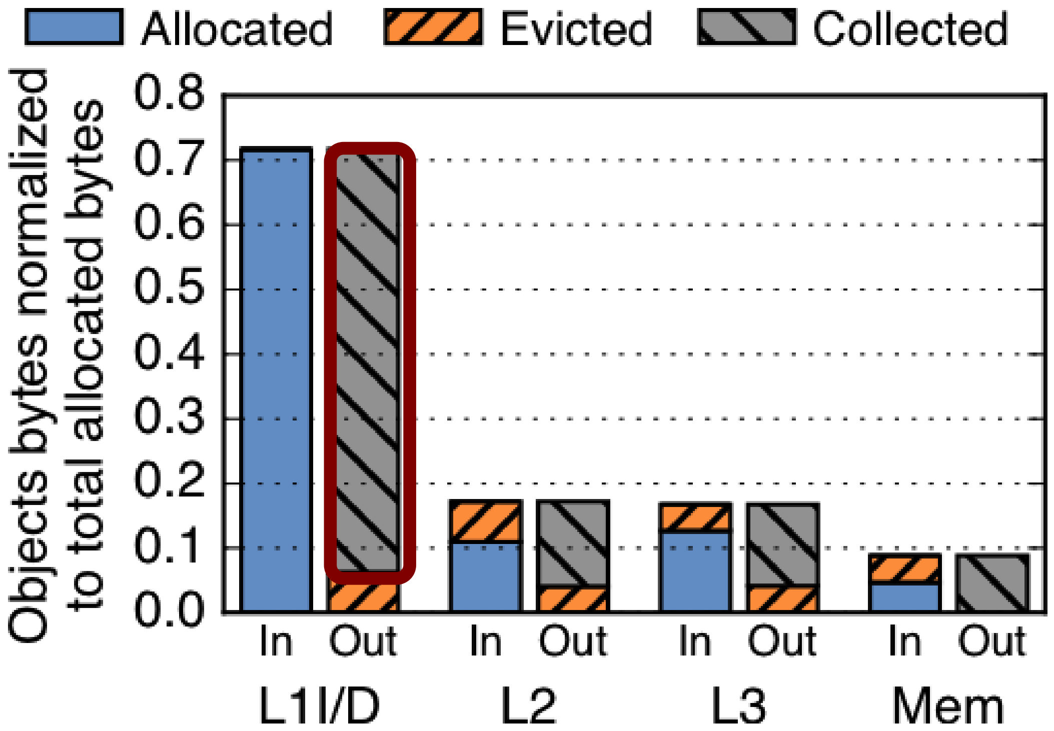

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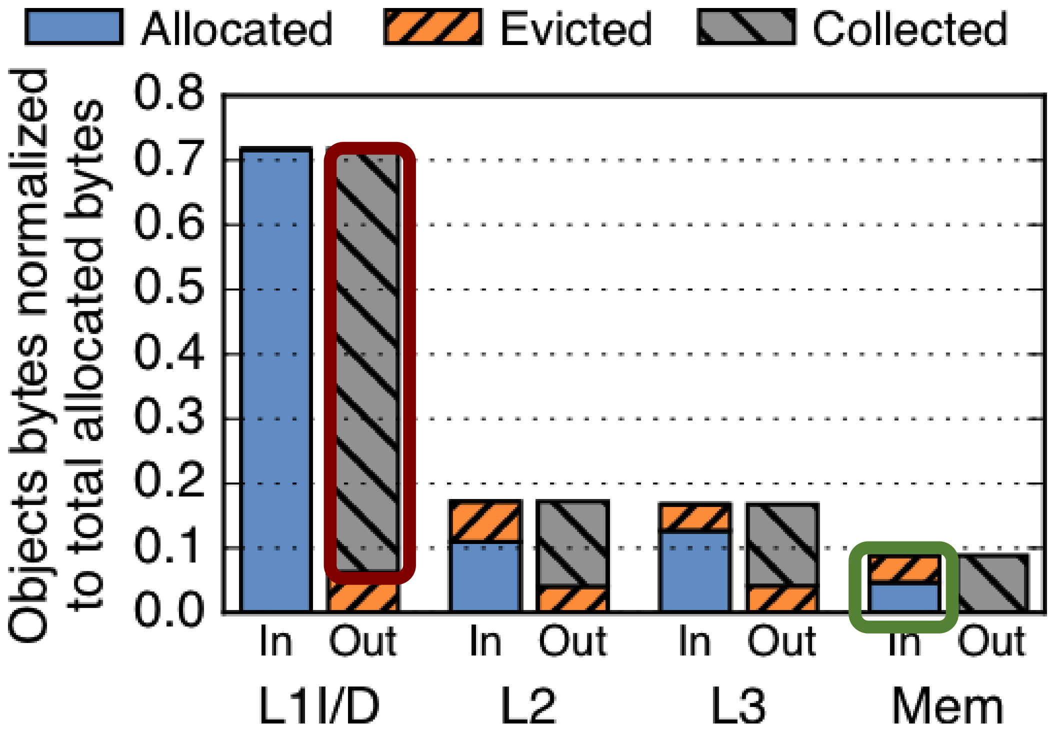

Most objects are collected in the L1 pad

90% of object bytes never reach main memory

See paper for additional features

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- Supporting large objects with subobject fetches

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- … and more details!

Evaluation

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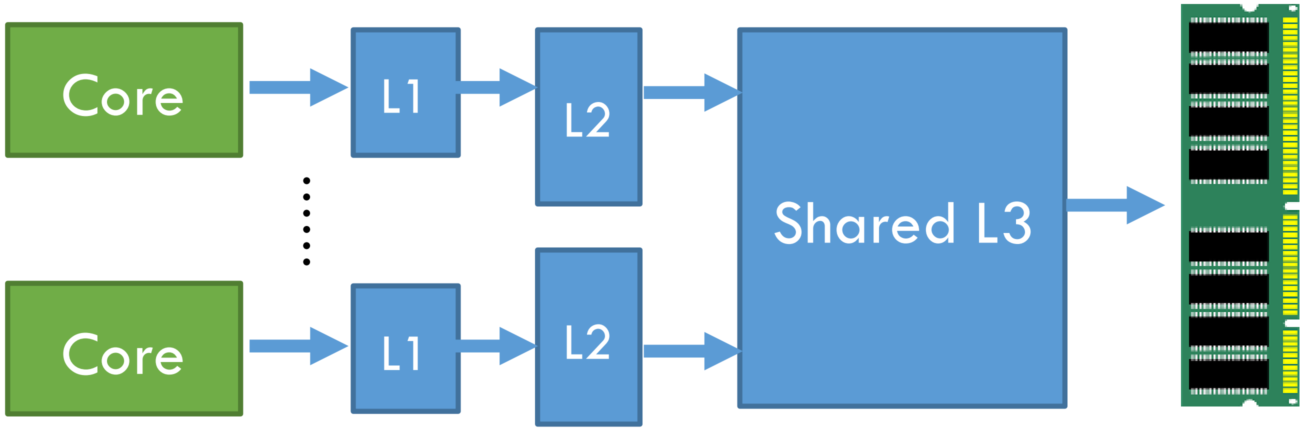

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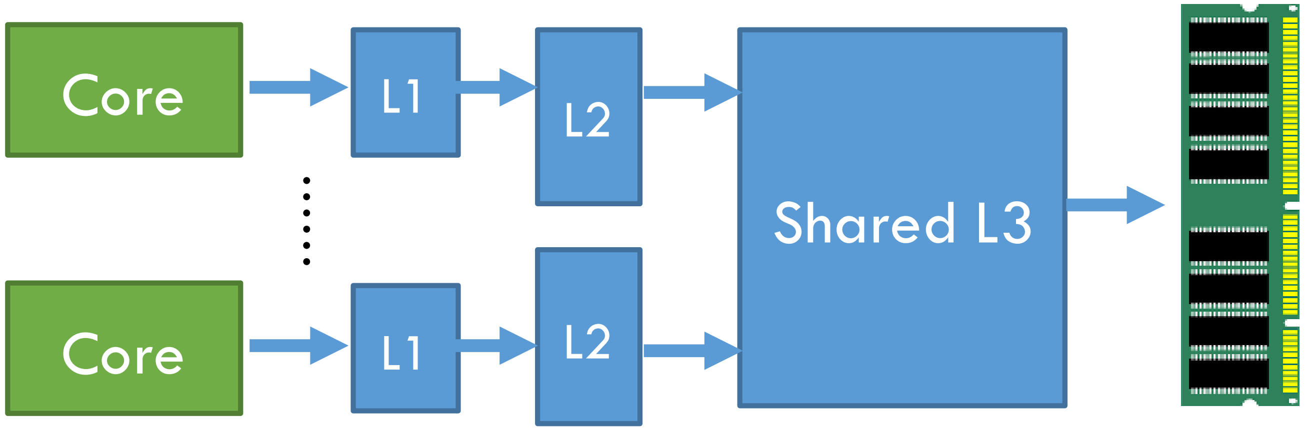

- Workloads
  - 13 Java workloads from Dacapo, SpecJBB, and JgraphT
  - JVM modified to use the Hotpads ISA

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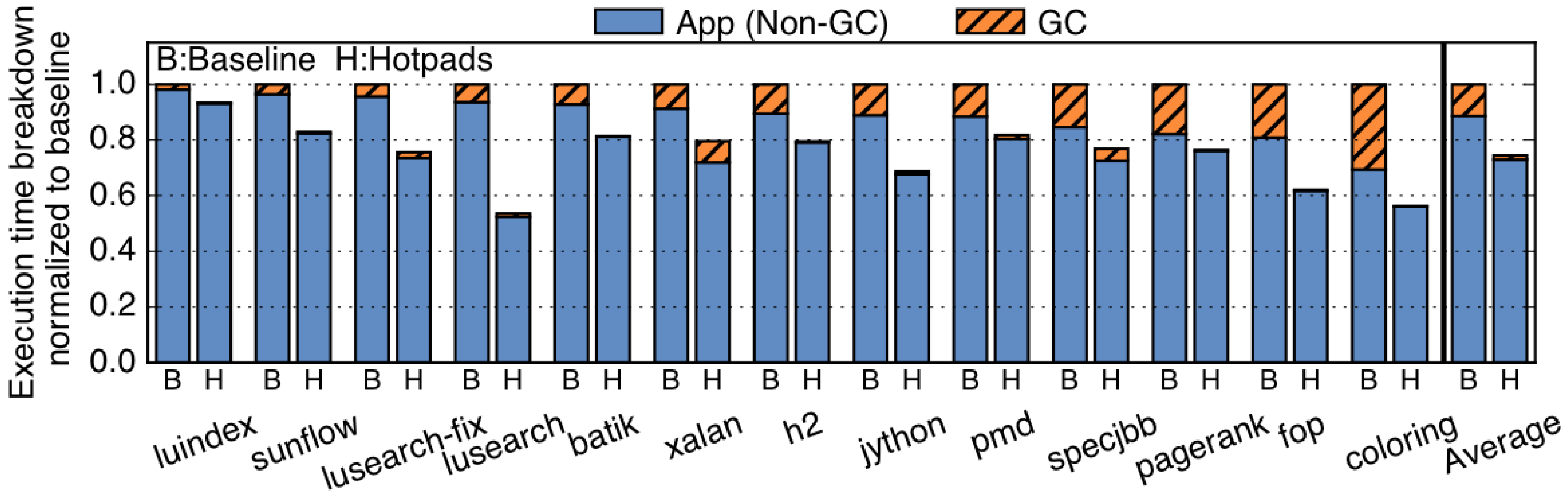

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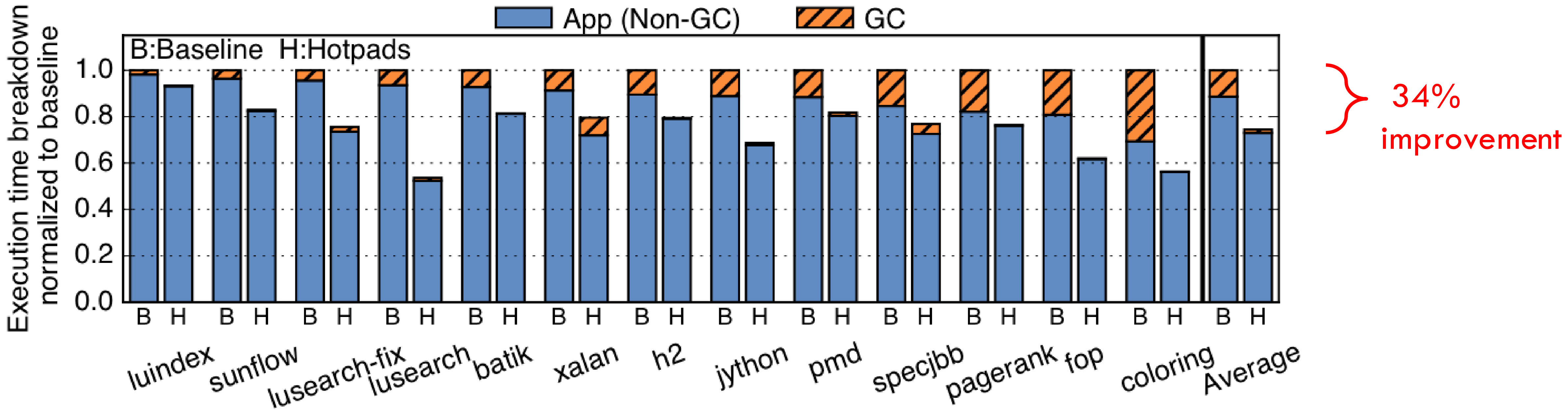

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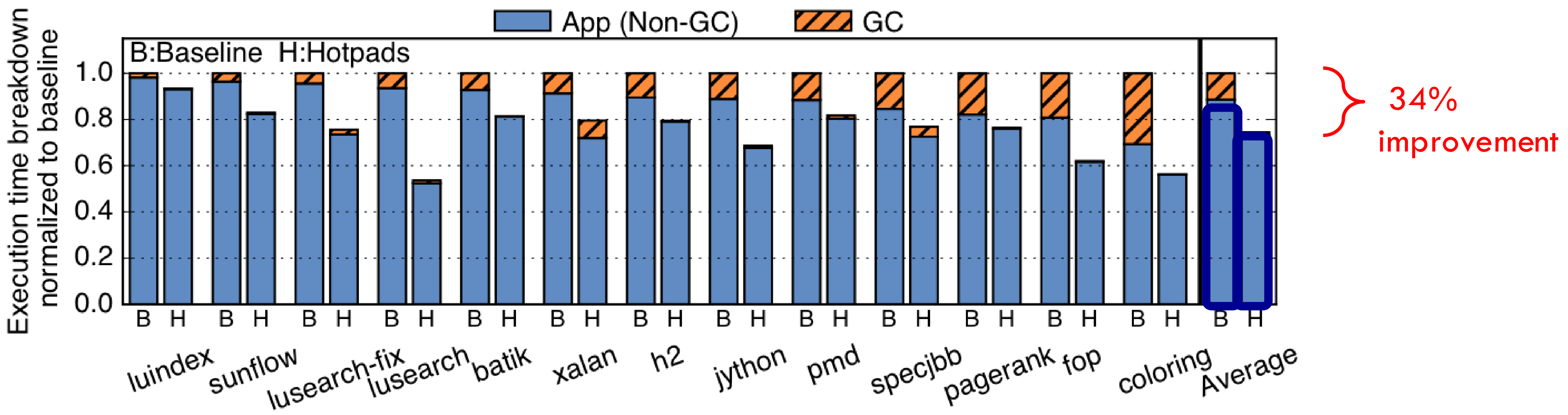

1. In-hierarchy allocation reduces memory stalls in application code

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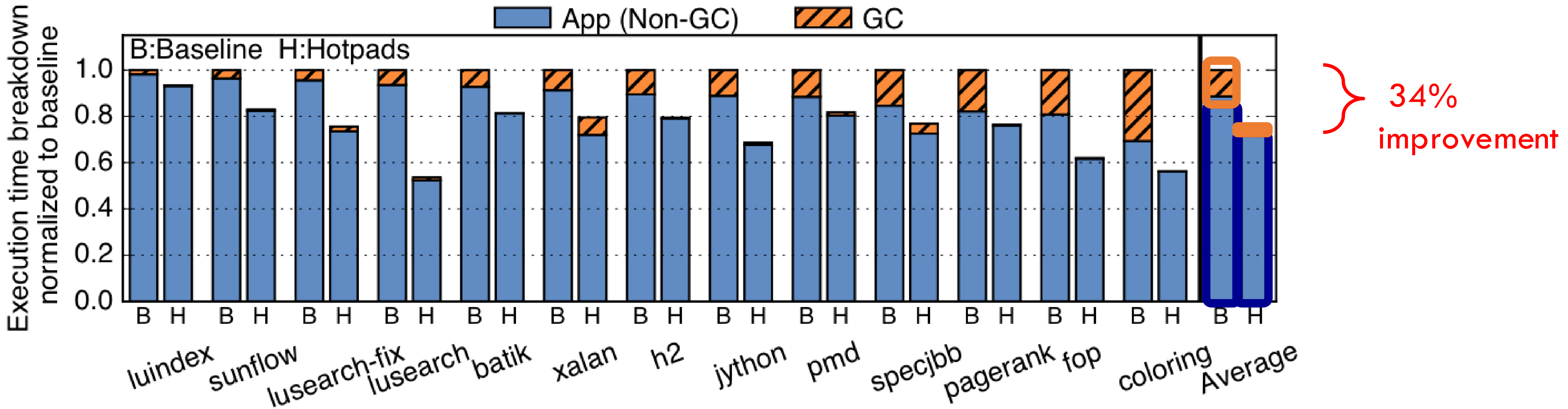

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2. Hardware-based collection-evictions reduce GC overheads

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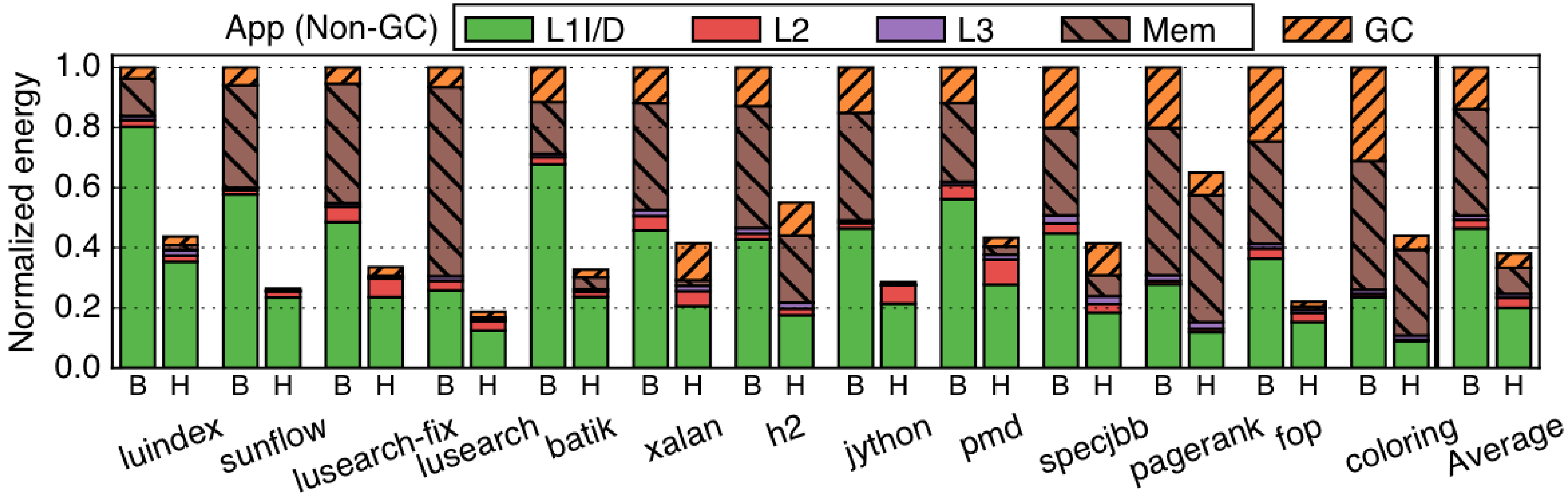

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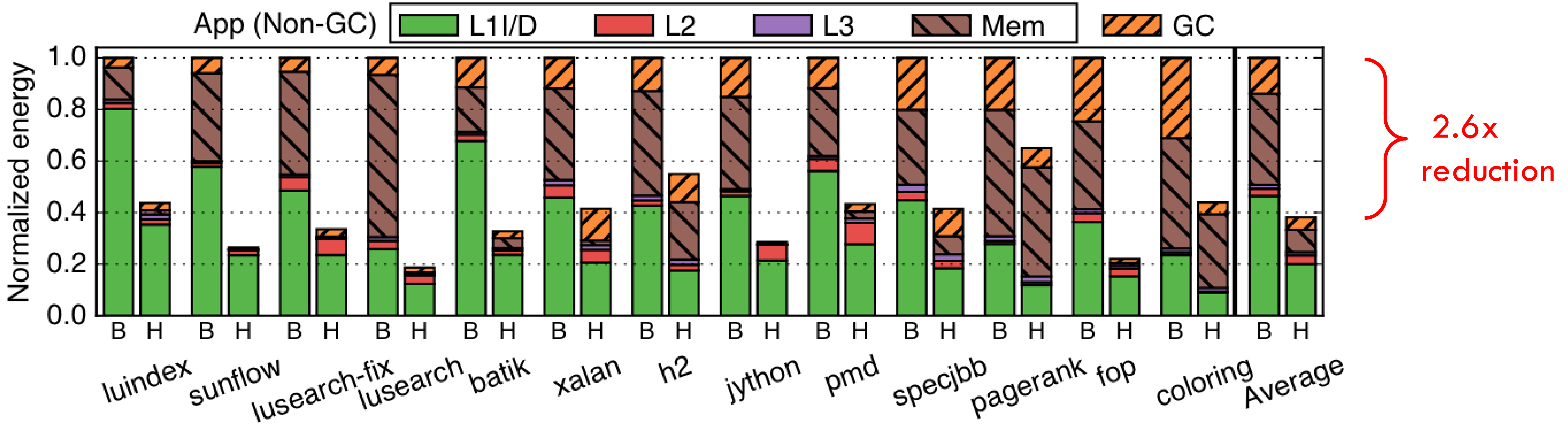

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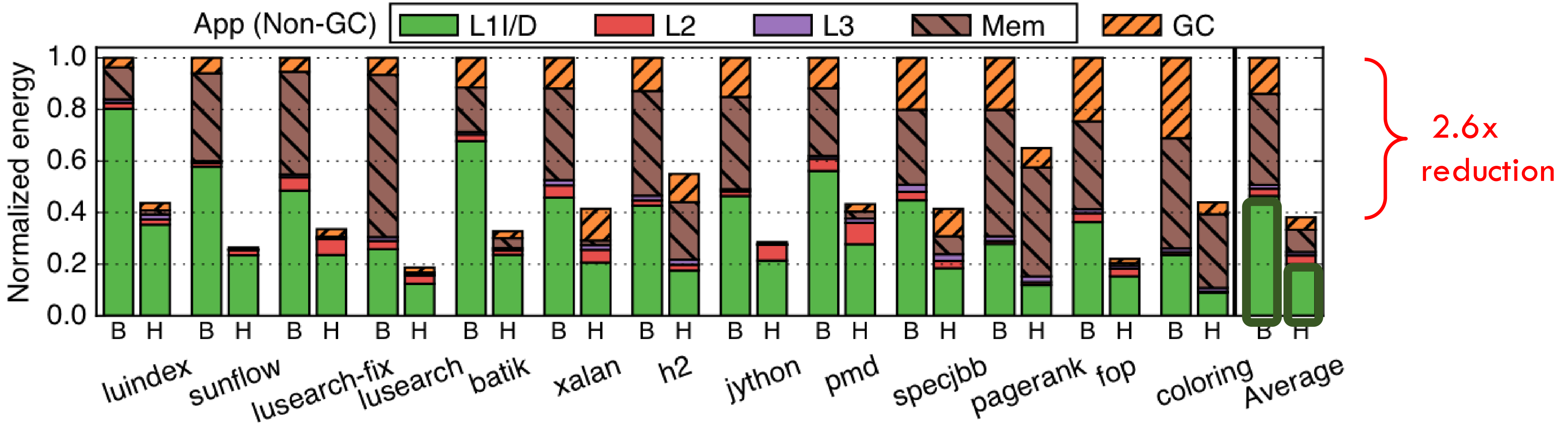

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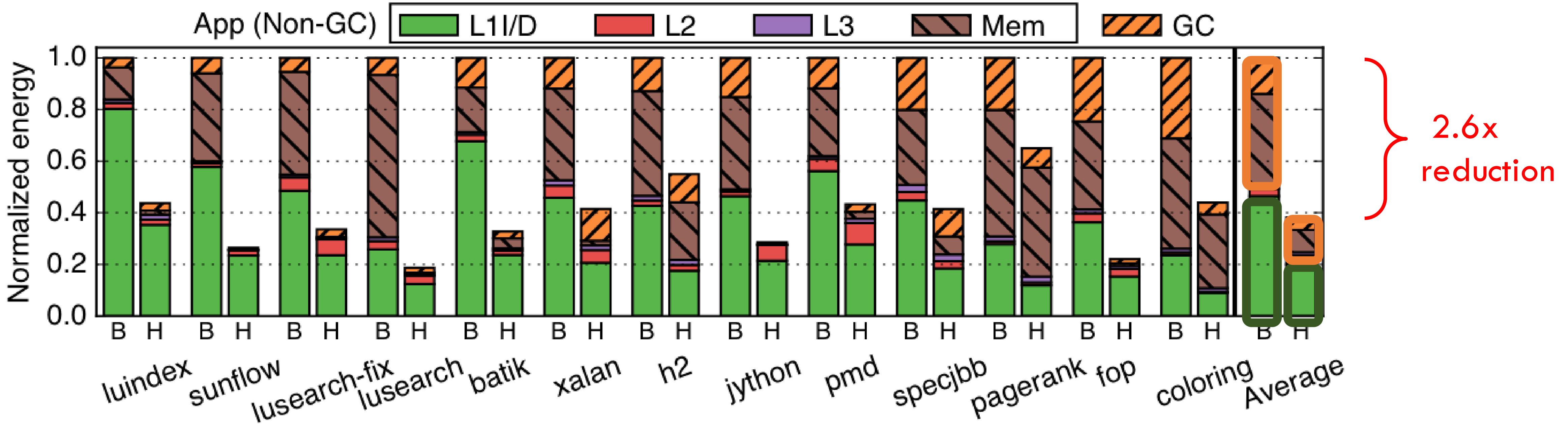

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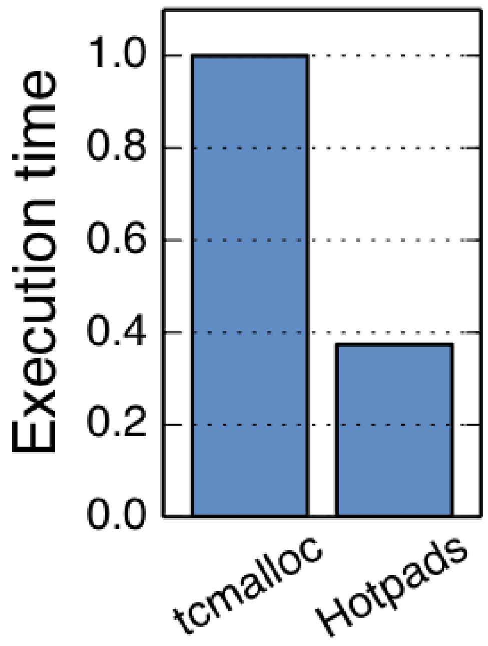

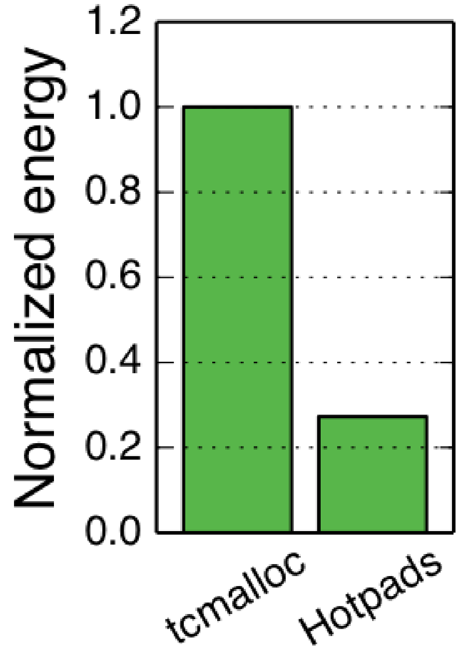

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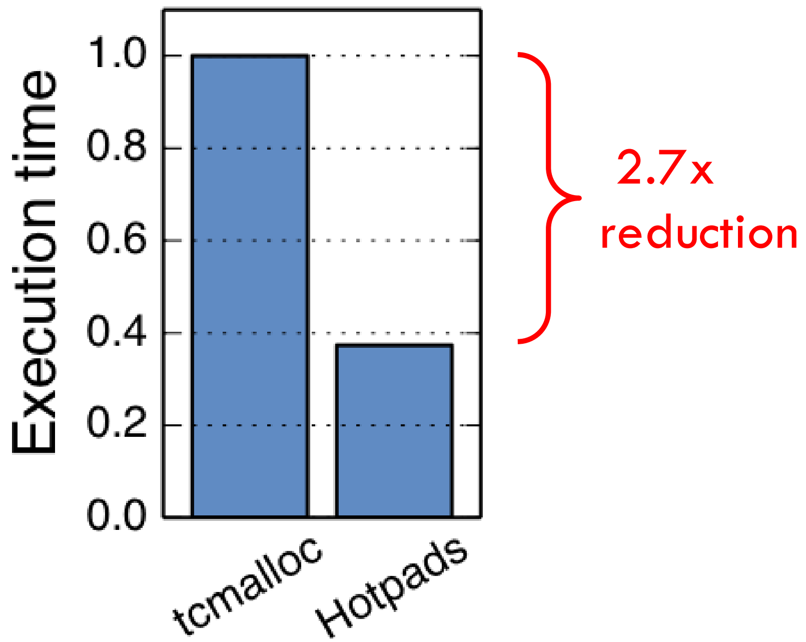

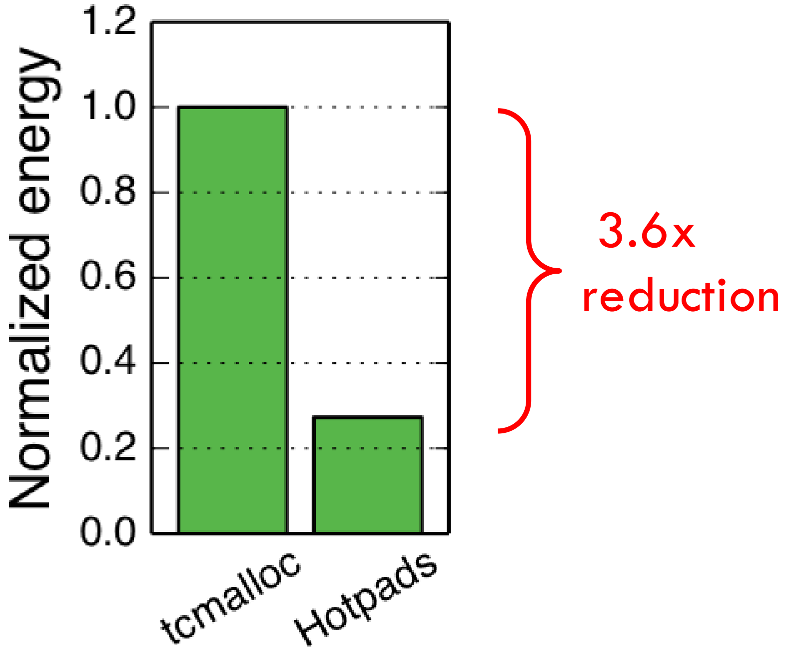

Hotpads improves performance and energy efficiency over manual memory management

See paper for more results

- Results for multithreaded workloads

- Detailed analysis of pointer rewriting and CEs

- Comparison with other cache-based techniques
  - Enhanced baseline using DRRIP and stream prefetchers
  - Cache scrubbing and zeroing [Sartor et al., PACT'14]

- Legacy mode performance on SPECCPU apps

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Thanks! Questions?

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